Benchmark Profiler Field Manual

FHWA Project
Improving the Quality of
Pavement Profile Measurement

Version 2.3

Christopher B. Winkler,
Steven M. Karamihas, Mark E. Gilbert, and Michael R. Hagan

University of Michigan Transportation Research Institute

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16. Abstract

This document describes the design and operation of the Federal Highway Administration's (FHWA) "benchmark profiler." The benchmark profiler is a three-wheeled, self-propelled cart equipped with an instrumentation set that allows it to make highly accurate, highly repeatable measurements of road surface profiles. The development of the benchmark profiler was supported by Transportation Pooled Fund Study TPF-5(063) "Improving the Quality of Pavement Profiler Measurement." In particular, the study sought to establish a benchmark testing procedure for verifying the repeatability and accuracy of candidate reference profilers. This document describes the benchmark profiler and its operation, and is meant as a users' guide for future experiments. A companion document ("Benchmark Testing Plan") describes the full experimental procedure.

This document provides instructions that describe: (1) theory of operation of the benchmark profiler, (2) field operation of the device in various modes, (3) operation of the reference laser, (4) a detailed measurement procedure, (5) data handling, (6) key components, and (7) routine maintenance.

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1. INTRODUCTION AND THEORY

This document describes the design and operation of the Federal Highway Administration's (FHWA) *benchmark profiler*. The development of the benchmark profiler was supported by Transportation Pooled Fund Study TPF-5(063) "Improving the Quality of Pavement Profile Measurement." In Study TPF-5(063), twenty state highway agencies and the FHWA pooled their resources and technical talent to, among other priorities, identify and develop multiple *reference profilers* for obtaining profile measurements that meet key requirements of accuracy and repeatability. In particular, the participants in the study sought to establish a *benchmark* testing procedure by which the *benchmark profiler* would provide the "ground truth" profiles against which the measurements of candidate *reference profilers* would be evaluated. In turn, participants could select a *reference profiler* that satisfied the requirements as a portable and efficient standard to use locally for verifying production profilers.

FHWA Western Federal Lands Highway Division (WFLHD) Agreement Number 04-A-17-0002 produced the "Critical Profiler Accuracy Requirements" report. This report defined a benchmark testing procedure for candidate reference profilers, but it did not provide a design for the benchmark profiler itself. Subsequently, FHWA Contract DTFH61-07-C-00024 supported the design and development of the benchmark profiler. The contract also included two profiler comparison experiments, in which the benchmark profiler provided ground truth measurements for verification of candidate reference profilers. These experiments were performed in October 2009, and September, 2010, at the Mn/Road research facility and a profiler certification section in Wisconsin.

During the two comparison experiments, the developers of the benchmark profiler identified several potential improvements to operational aspects of the device. In addition, the benchmark profiler was sufficiently successful that the issue of its use by operators other than the developers was raised. In response, FHWA Contract DTFH70-10-E-00019 "Development and Refinement of a Benchmark Profiler System" supported several upgrades to the benchmark profiler, which were made in parallel to the second profiler comparison experiment. While the basic measurement concept and the major components of the benchmark profiler remained the same, the contract supported upgrades to the benchmark profiler's host cart, operational logic, and supporting hardware. The contract also required the development of this document, which enables the operation of the benchmark profiler by personnel other than the device's original developers.

1.1. The Benchmark Profiler — Physical Description

The benchmark profiler is a three-wheeled, self-propelled cart equipped with an instrumentation set that allows it to make highly accurate, highly repeatable measurements of road surface profiles. It is intended for profiling new roads in good condition. It works in concert with a high quality, ground-based spinning laser whose beam, projected onto three "laser targets" on the profiler, is observed by one of two on-board machine vision systems. This system provides a stable reference plane above the road surface to which the road profile, measured by a RoLine 1130 scanning laser on the profiler, is referenced. When performing profile measurements, the profiler is fully autonomous, controlled by

the computer of an on-board UMTRI data acquisition system (DAS) and guided by the second machine vision system, which observes a *guidance* measuring tape laid down on the road surface immediately adjacent to the section of the surface being profiled. For transport other than actual profile measurement, the profiler is controlled by an operator using a joystick.

Figure 1.1. The benchmark profiler tracking the guidance tape autonomously with the spinning laser in the foreground

The key elements of the measurement system, the RoLine, the laser targets, and the two machine-vision cameras, are all mounted on a single, rigid "backbone" structure. In normal use, this instrumentation *kernel* as well as all the other technical elements of the profiler are fully enclosed in an insulated, aluminum cover. Photographs of the benchmark profiler, with and without its cover in place, appear in figure 1.2. Major components are labeled in each photo. Figure 1.3 presents a plan view showing the location of the major elements of the profiler. General specifications of the profiler appear in table 1.1.

1.2. Theory and Detail of the Measurement System

The benchmark profiler uses the same measurement concept as a rod and level. A rod and level establishes the elevation at a given location by measuring the distance to the road surface beneath a stable reference height along a vertical rod. Like the rod and level, the benchmark profiler measures the distance from a stable reference plane to the ground at each location. However, it performs this task with a higher degree of automation to overcome the slow measurement speed and long recording
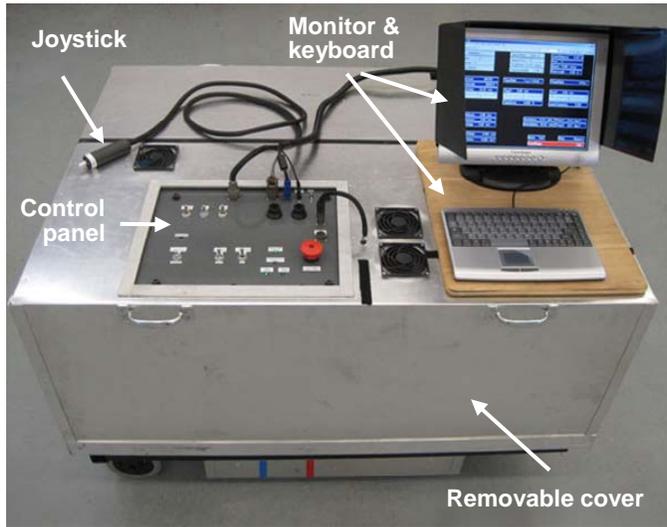
a. From the left, with its cover in place
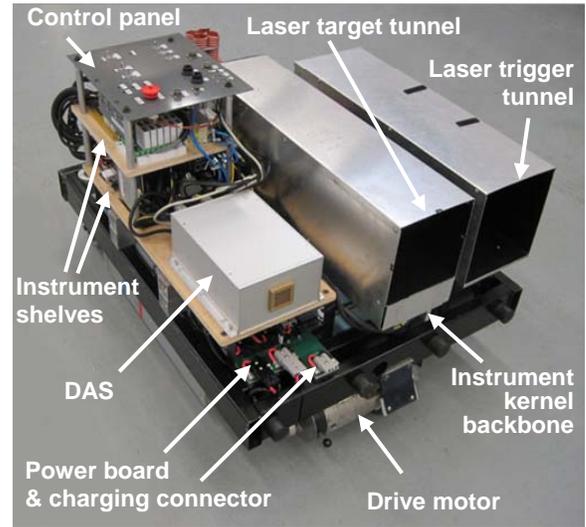
b. From the left rear, with its cover removed

Figure 1.2. The benchmark profiler
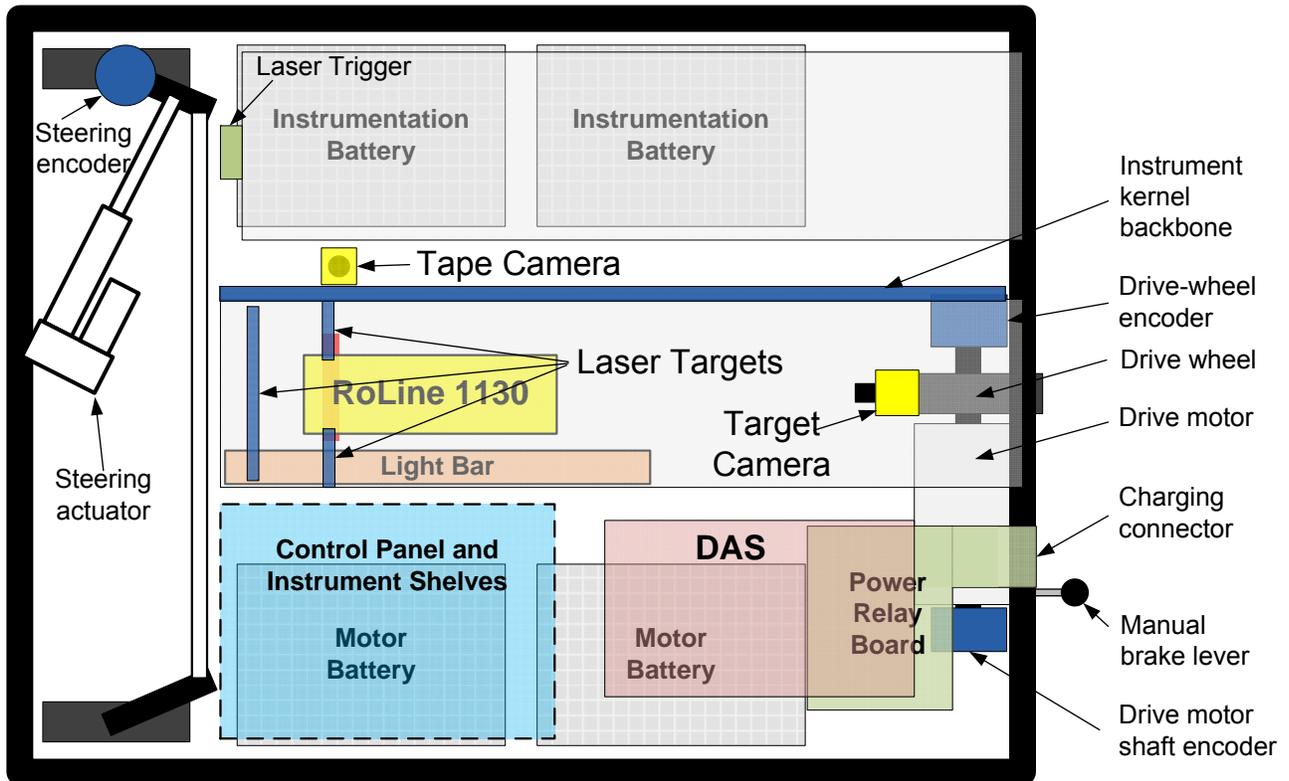
Figure 1.3. A schematic diagram of the major elements of the benchmark profiler in plan view

interval typically associated with a rod and level survey. In addition, a line laser replaces the function of the rod foot. This gives the device a more appropriate footprint.

Table 1.1. Benchmark profiler specifications

Configuration: tricycle; two front steering wheels; one rear drive wheel

Dimensions:		*Length*	*Width*	*Height*
	with cover	48-¾ in.	39 in.	29-¼ in.*
	without cover	48-¾ in.	34-½ in.	28-¾ in.

* Without keyboard and monitor; with monitor upright, add 13-½ in.; with monitor folded, add 3-5/8 in.

Wheelbase: 40 in.
Front track: 28 in.
Weight: Complete with cover and keyboard/monitor: 450 lb.
 Cover: 38 lb.; keyboard/monitor: 13 lb.
Steering: Zero caster; zero camber; Ackerman linkage; electric servo actuator.
 Minimum turn radius at the inside front wheel: 150 inches.
Drive: 22 volt/15 amp DC motor with integral gear reduction and integral friction brake.
Speed: 2.5 to -2.5 ft./sec. under operator control.   ± 0.15 m./sec. while profiling.
Power: Instrumentation: Two 12-volt, 63-amp-hr., gelled-electrolyte, lead-acid batteries.
 Steering and drive: Two 12-volt, 47.5-amp-hr., gelled-electrolyte, lead-acid batteries.
Control: Operator mode: joystick control of steering and speed
 DAS/Setup mode: DAS control of steering; joystick control of speed
 DAS/Test mode: DAS control of steering and speed
Primary instrumentation:
 Roadway profile: Selcom RoLine 1130
 Reference height, pitch and roll: Cognex In-Sight Micro 1400 camera (#1) in combination
 with ground-based Hamar L-740 spinning laser, see sections 1 and 3;
 Longitudinal and lateral positions: Cognex In-Sight Micro 1400 camera (#2);
 Longitudinal position: BEI HS35 incremental optical encoder
Secondary Instrumentation:
 Speed-control servo feedback: BEI HS25 incremental optical encoder.
 Steer-control servo feedback: potentiometer integral in steering actuator; BEI H20
 incremental optical encoder.

1.2.1. The Instrument Kernel

Figure 1.4 shows details of the measurement kernel of the benchmark profiler, exposed by removing the sheet-metal tops of the laser-target and laser-trigger tunnels and the floor of the target tunnel. In the photo, the front end of the profiler appears at the top and the rear end appears at the bottom. The kernel includes three instrumentation systems:

- *Body orientation and vertical position* — The beam of a spinning laser, mounted on a ground-based tripod positioned behind the profiler, defines the stable reference
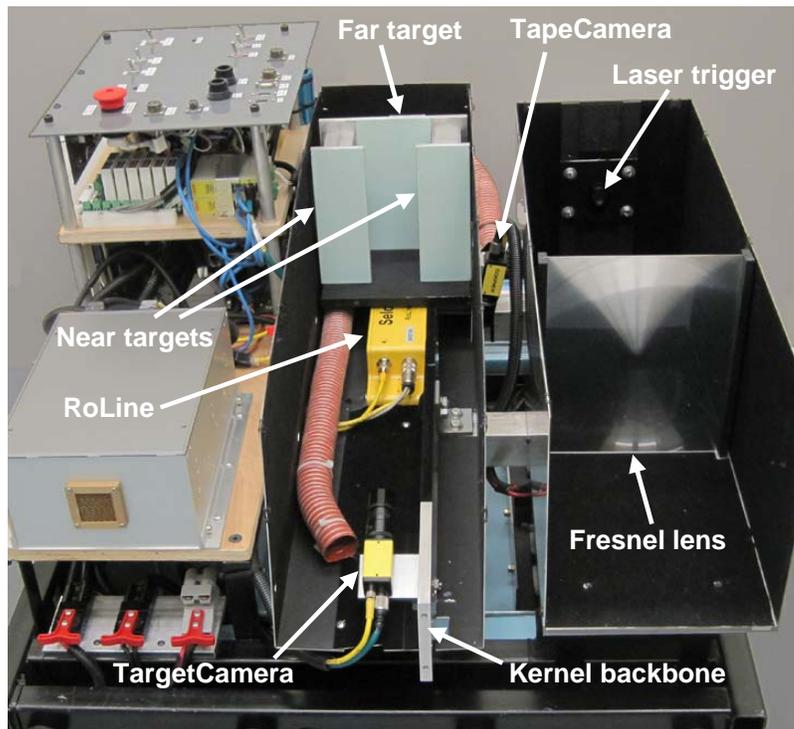
Figure 1.4. Features of the instrument kernel and the laser trigger

plane above the road surface. The beam from this spinning laser is projected onto three targets mounted on the kernel. A machine vision camera (TargetCamera) senses the beam on the targets to establish the height as well as the pitch and roll angles of the kernel relative to the reference plane. Two *near* (i.e., near to the TargetCamera) targets, side by side on the same plane, serve for detection of roll angle (i.e., rotation about the longitudinal axis), and the third, *far* target is separated longitudinally for detection of pitch angle (i.e., rotation about the lateral axis). The vertical position of the laser sweep at a reference (central) lateral position between the near targets establishes the reference height.

- *Vertical range to road* — A RoLine laser measures the vertical distance (i.e., range) between a reference location on the kernel and the road surface. The RoLine's range measurements are in the plane of the two near targets. The RoLine provides several values over a wide footprint. A bridging algorithm reduces the values that fall within a given area of interest to a single range value.

- *Body location on the ground* — A second machine vision camera (TapeCamera) detects the lateral position and yaw angle of the profiler relative to a nylon-coated steel tape fixed to the road. These readings provide feedback to a steering control system that maintains a consistent lateral position and yaw orientation of the kernel relative to the tape as the profiler moves forward.

Like the level in a rod and level measurement system, the spinning laser provides a consistent vertical reference plane for the device. The device establishes the distance from the reference plane to the road surface using two dimensions. The first is the vertical position of the spinning laser on the near targets compared to a reference point fixed on the device kernel. The second dimension is the distance from the reference point to the road surface, which is established by the vertically oriented RoLine ranging laser. Gross longitudinal distance is established using the steel tape, and distance between reference points on the tape is estimated using pulses from an encoder attached to the drive wheel.

1.2.2. Orientation and Vertical Position of the Profiler

A spinning laser provides a stable reference plane for the profiler. A Cognex machine vision system measures the height and orientation of the device kernel relative to the reference plane by analyzing the image of the laser beam as it is projected on three targets. The system includes an InSight Micro programmable camera and special image processing routines. (See figure 1.4.)

Screen Image

Figure 1.5 shows an image, captured by the TargetCamera, of a laser sweep across the three targets on the device kernel. Since the exposure time for each image encompasses the entire sweep, the laser spot appears as a line on each target. For each segment of detected light, the vision system derives the position (height and slope) of the corresponding target by defining a best-fit line along the transition between light and dark pixels above and below each line. The camera's algorithm defines each of these lines by identifying their end points. The end points of the center line of the laser image on each target is determined by averaging the end points of the upper and lower transition lines. Finally, the four end points for lines on the near targets are used to determine a best-fit line for the

near plane. Then additional, real-time, imbedded processing routines in the camera derive three quantities relative to the laser reference plane:

Figure 1.5. Image of the laser targets with a reference laser line

- *Kernel height* is derived by determining the intersection of best-fit line on the near plane with a vertical line through the center of the image.

- *Kernel roll angle* is derived using the slope of the best-fit line on the near plane.

- *Kernel pitch angle* is derived by comparing the kernel height as determined in step (1) with the kernel height determined in a similar fashion using the line of the far plane (inner screen).

The system collects and processes these images when it is prompted by a trigger, as described below. The overall image covers an area about 200 mm. (8 in.) wide and 140 mm. (5.5 in.) high, and 640 pixels wide and 480 pixels high. This permits vertical resolution of each pixel on the order of 0.3 mm. However, the ability to judge a degree of illumination in each pixel and the use of a linear fit over a significant width permits the system to resolve height to a much finer level of precision.

The camera lens is equipped with two special filters that limit the incoming light with a pass-band that is just 13 nm wide and encompasses the red (658 nm) of the spinning laser. A light tunnel with dark sides further reduces contamination of the images by ambient light. (See figure 1.2.b.) Successful detection of the laser image as it sweeps past the target also depends on careful control of the gain applied to the light sensed by the camera's detector, as well as real-time control of camera exposure time; calculation of both gain and exposure is accomplished in the TargetCamera based on the current distance from the spinning laser.

Trigger

As shown in figure 1.2.b and figure 1.4, the profiler includes a second light tunnel for triggering the TargetCamera. A silicon photo diode at the end of this light tunnel detects the laser beam milliseconds before its arrival on the laser targets. A Fresnel lens focuses the incoming laser light toward the diode to help guarantee that the beam is detected. The system high-pass filters and amplifies the signal from the diode. As soon as the laser beam is detected, a timing pulse is provided to the DAS. After a very short delay, the DAS triggers the TargetCamera to collect and process an image of the targets.

Spinning Laser

The spinning laser is a Hamar Laser L-740. As modified for use with the benchmark profiler, this unit sweeps at a rate just under 18 full rotations per second. It projects a collimated beam about 4.06

mm. in diameter. The laser diode projects light at a wavelength of 658 nm, and projects 3 mW of power. The specifications list laser plane flatness of 0.5 arc sec. and beam stability of 0.2 arc sec./hr./degree F. More importantly, measurements of the laser beam by the vision system under favorable atmospheric conditions confirmed stability of the beam of 0.08 mm. at a distance of 37 m. when the profiler was stationary.

Laser Set-Up

Each section is measured in multiple segments, depending on lighting and atmospheric conditions. For each segment, the spinning laser plane is established with a roll angle relative to gravity at or very near zero. In addition, the plane is adjusted in pitch to roughly follow the grade of the road over the segment of interest. The overall "grade" of the reference plane in each set-up is used to resolve the profile elevation values to a flat reference plane. Segment endpoint elevations are measured using a conventional rod-and-level survey to determine the height differences established by the pitch of the spinning-laser.

1.2.3. Vertical Range to the Road

Vertical range to the road surface is measured using a RoLine 1130 laser sensor. The RoLine 1130 projects a fan-shaped beam of laser light downward toward the road in a manner to illuminate a *lateral line* on the road surface. Reflections from this line are analyzed to produce discrete, evenly spaced vertical-range measurements along the line. The RoLine is fixed within the device kernel of the benchmark profiler such that the fan of laser light and, hence, the vertical-range measurements are in the same plane as the side-by-side, near targets used to detect the reference plane define by the spinning laser.

The RoLine is mounted 325 mm. above the nominal ground plane. At this standoff height, the fan of laser light provides a line spread over a width of 110 mm. from which is derived 150 individual, evenly spaced data points. On the benchmark profiler, this measurement process is repeated at approximately 429 Hz. Given the benchmark profiler's nominal speed of 0.15 m./sec., this 429-Hz. rate results in approximately 2.86 data lines per millimeter of travel along the road surface.

The 110-mm. wide footprint of the RoLine is arranged to contain a 70-mm. wide track of interest, a nylon-coated steel tape (for reference), and some extra width on the outsides to accommodate the small, lateral wander of the profiler. Figure 1.6 shows the nominal layout of the track of interest and the steel tape within the RoLine laser footprint. A servo control system, described below, steers the profiler to ensure that the track of interest and the left edge of the steel tape always appear within the RoLine footprint. In the neutral position, the footprint includes 13 mm. of extra width to the left of the track of interest, and about 6 mm. to the right of the steel tape. This arrangement allows up to 13 mm. of wander of the profiler without missing any of the track of interest. (In use, steering offset typically remains within ±8 mm.) Figure 1.7 presents a three-dimensional representation of RoLine measurements of a 110 mm. x 110 mm. section of new, longitudinally tined road surface, in the vicinity of a slab joint, and with the steel tape along the edge of the measurement area.
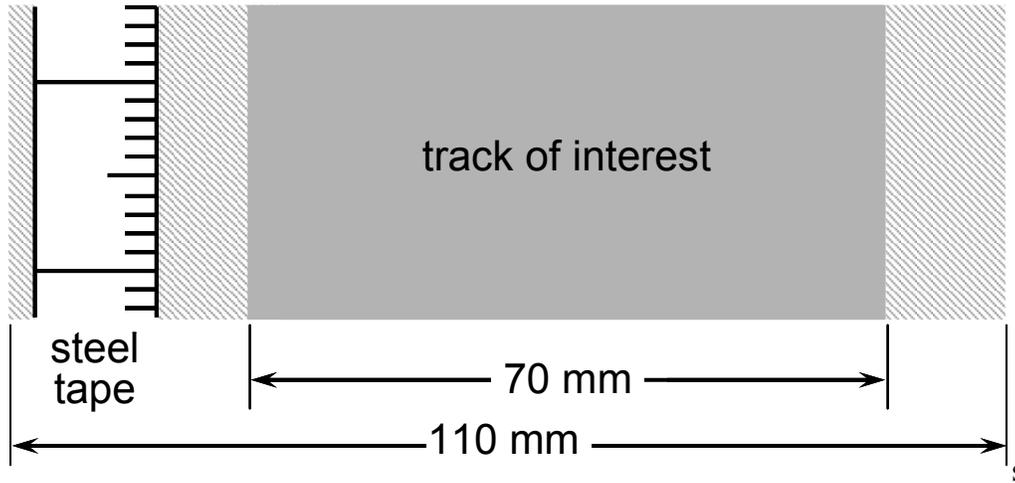
Figure 1.6. Layout within the RoLine footprint
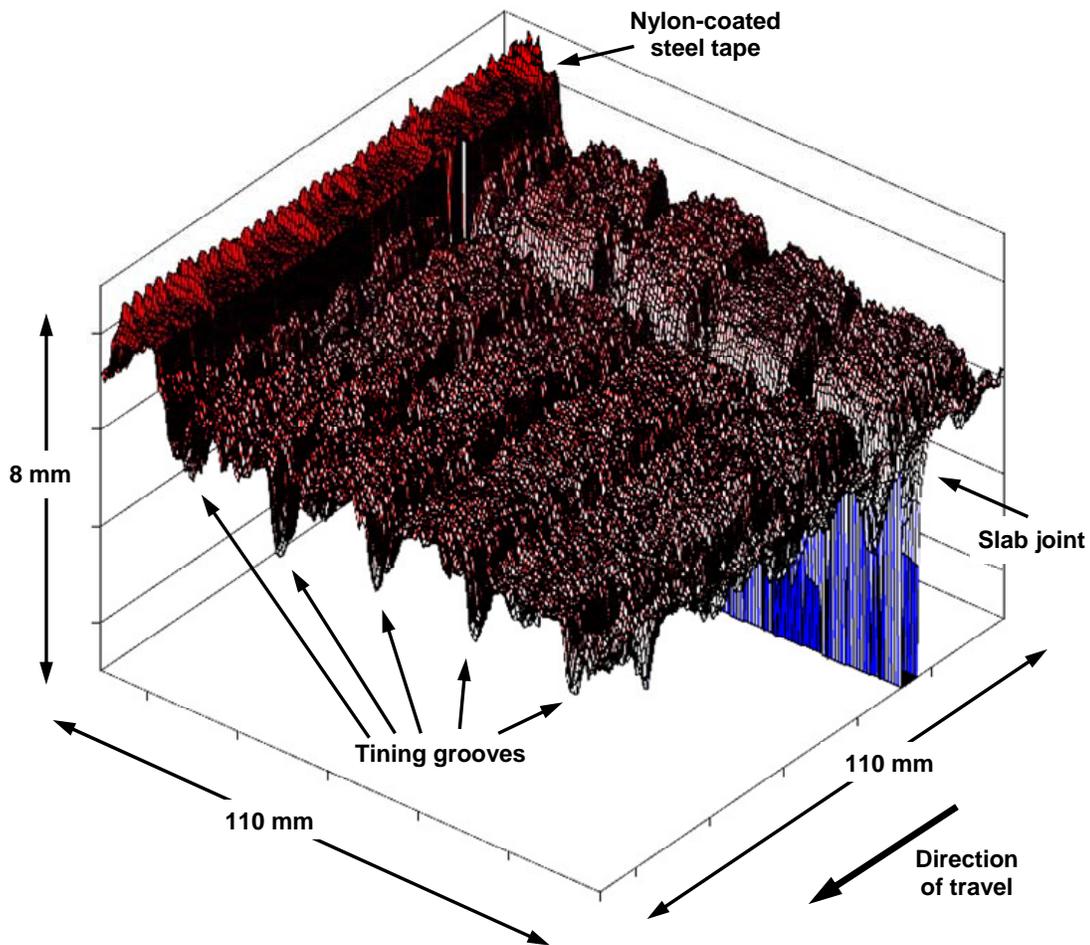
Figure 1.7. Surface plot of RoLine measurements of a new, longitudinally-tined road surface
314 lines x 150 points/line = 47,100 points

The measurement track of interest is defined as the 95 data points ranging from 13 mm. to 83 mm. to the left of the left-most edge of the steel tape. Typically, the location of the tape edge within the footprint is obvious. Figure 1.8 presents a plot generated from the 150 data points of a single line of RoLine data in which the position of the steel tape is obvious next to a relatively smooth road surface.
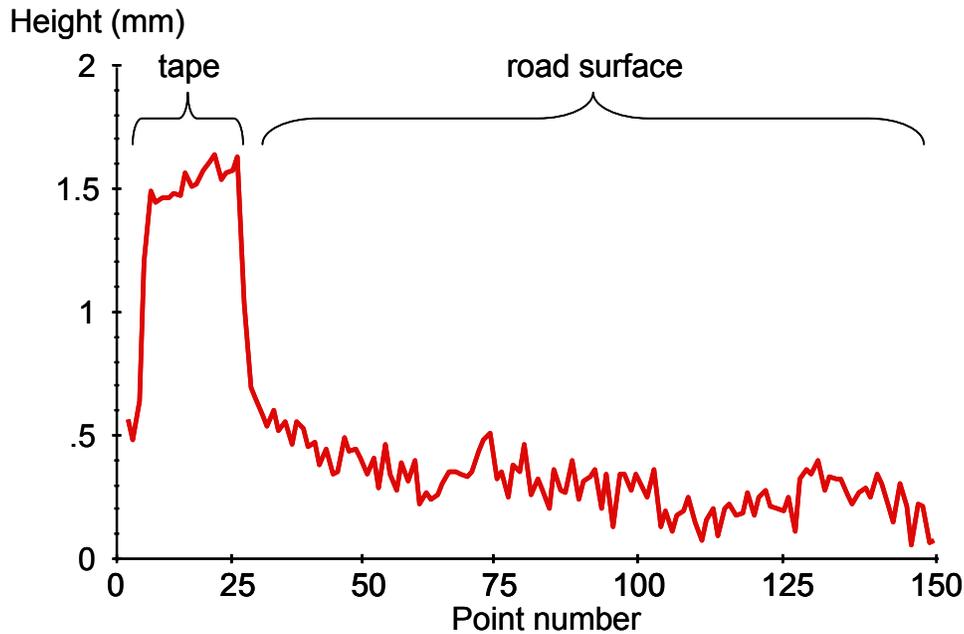
Height (mm)

Figure 1.8. Sample RoLine output

The 95 points within the track of interest are reduced to a single range value using a bridging filter. The filter establishes height within the line of interest by seeking the elevation that would produce an average "penetration" upward of 0.7 mm. Thus, the filter is sensitive to positive texture, but it ignores narrow downward spikes within each line of output from the RoLine.

Each value of range downward to the road surface is expressed relative to a reference point on the kernel. These are combined with the height of the reference plane above the reference point on the kernel. Together, these values provide the elevation of the road relative to the spinning laser reference plane. Each elevation value is eventually resolved to an earth-based coordinate system using the measured orientation (pitch and roll) of the profiler and the pitch angle implied by the segment endpoint elevations. Small angle assumptions are applied in this part of the process.

The RoLine laser provides about 429 "lines" per second at a constant rate. Since the device moves very slowly (150 mm./sec.) this is an excessive amount of data, corresponding to nearly 3 readings per millimeter. The final benchmark profile is decimated to a single reading per 5.08 mm. of longitudinal distance by using the same bridging filter that is applied to each transverse profile. The filter is applied over 76.2 mm. of longitudinal distance.

1.2.4. Location of the Profiler on the Ground

A nylon-coated steel tape fixed to the test section parallel to the longitudinal track of interest provides a location reference for the benchmark profiler. A machine vision system measures the yaw angle, lateral position, and longitudinal position of the profiler relative to the tape. The system includes a downward facing InSight Micro programmable camera (TapeCamera) and special image processing routines. The camera lens is fitted with a optical notch filter that removes the intense red of the RoLine laser from the camera image. The field of view of the camera is illuminated by two Cognex LED light bars.

Figure 1.9 provides a sample image of the ground and steel tape from the TapeCamera during automated operation. The image processing routines search the captured image for a section of the image that best correlates to a "trained image" of a segment of the steel tape. This determines the lateral, longitudinal and angular position of the chosen segment within the captured image.
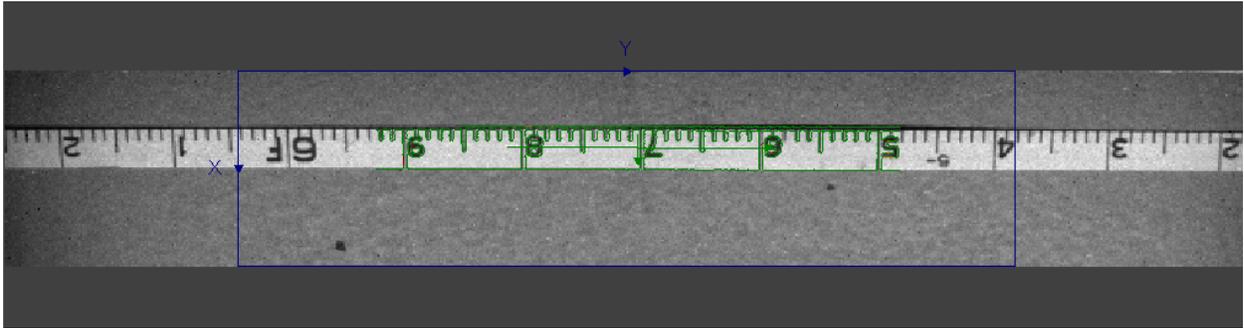
Figure 1.9. An example image from the TapeCamera with trained-pattern match

Whenever the appropriate range of numbers appears in the captured image, the sample pattern is found with a very high correlation score. (The score for the match of figure 1.8 in 98.2%.) If the appropriate range does not appear in the image, the program still detects the tape, but at a lower correlation score, because, while the proper digits do not appear, the general hash mark pattern on the captured image and the hash mark pattern in the target image still correlate well. In the latter case, the lateral position and yaw angle are correct, but the longitudinal position is not. The program of the TapeCamera provides lateral position, yaw angle, longitudinal position and the correlation score to the DAS, regardless of the correlation level.

The TapeCamera provides readings asynchronously at approximately 12 Hz. The search routines tend to take longer when the actual target is not present and when the yaw angle is non zero.

In post processing of the profiler's location data, those longitudinal measures accompanied by a high correlation score are used to establish the longitudinal progress of the profiler in one-foot increments. Between each of these increments, the longitudinal position is determined to much finer resolution using a 2000 pulse-per-revolution encoder driven directly by the drive wheel (as opposed to the encoder mounted on the motor shaft which is used for speed-control feedback).

1.2.5. Lateral Position and Steering Control

A linear actuator steers the benchmark profiler through a conventional Ackerman steering system. Figure 1.10 presents a top view of the steering linkages. A PID servo controller board controls the actuator. Upon boot of the controller, steering is placed on center using position feedback via a potentiometer internal to the actuator. When it is determined that steering is on center, feedback is switched to the steering encoder. In manual operation, steering (and drive) commands are provided using the hand-held joystick.

Figure 1.10. Top view of the steering system showing actuator, linkage, and encoder

During automated data collection, the DAS provides steering commands to a PID controller in order to maintain a consistent lateral position relative to a nylon-coated steel tape fixed to the ground. The profiler's lateral offset (from the desired position) and yaw angle are measured by the machine-vision system described above. Within the camera's program, these measures are processed, based on known dimensions and the kinematics of the profiler, to determine the appropriate steering command for eliminating lateral position errors. This command, along with the lateral position and yaw angle data (as well as longitudinal position and a correlation score), is sent to the DAS, which, in turn, forwards the steering command to the controller board. During testing in the forward direction, this automatic steering system typically maintained the desired lateral position of the profiler to within 1.5 mm. and yaw angle to within 1 degree. When traveling in the reverse direction, the system typically maintained the desired lateral position of the profiler to within 5 mm. and yaw angle to within 1 degree.

1.3. Profile Computation

Four measurement systems within the benchmark profiler provide the ingredients used in the calculation of profile: (1) the RoLine laser, (2) the machine vision system used to detect the reference laser on the near and far targets (i.e., the TargetCamera), (3) the machine vision system used to read the nylon-coated, steel guidance tape (i.e., the TapeCamera), and (4) the drive-wheel encoder. Each of these systems provides data at a different rate, and the machine vision systems do not provide data at a constant rate. Output from each of these systems is recorded in a different set of raw data files. Merging these data depends on using time from the DAS clock as a common signal. The DAS time associated with each data packet (e.g., the moment of exposure of a camera) is recorded along with the data from each system.

The TapeCamera's program provides the data needed to establish coarse (but accurate) longitudinal position of the profiler. This is merged with much more frequent readings from the wheel rotation encoder to provide longitudinal distance traveled by the profiler as a function of time every 0.01 sec. The TargetCamera provides orientation and elevation of the profiler compared to the reference plane. This and the longitudinal distance data are merged with data from the RoLine, which collects data at a much higher rate. The merging requires linear interpolation using the common signal from the DAS clock as a reference signal.

The merging process is complicated, and it produces a very detailed set of elevation and distance pairs at a constant time interval of about 429 points per second for each segment of profile. Precise segment endpoints are found by searching for the step change at reference plates placed on the road just outside the segment limits. Data from multiple segments are "sewn" together by adding a linear trend to each segment profile so that the endpoints have the elevation value measured in the rod and level survey. Once the profile of the entire test section is assembled, the longitudinal bridging filter is applied and the filtered profile is decimated to a final, constant distance interval of 5.08 mm.

Section 5 describes the analysis steps in more detail.

2. OPERATING THE BENCHMARK PROFILER

This section identifies the controls and input/output devices of the benchmark profiler and presents background information and instructions for operating the profiler manually in non-test situations and automatically under the control of the UMTRI DAS when making profile measurements.

2.1. Controls and Input/Output Devices

The benchmark profiler is operated and monitored through the use of five "sets" of controls shown in figure 1 and listed below.
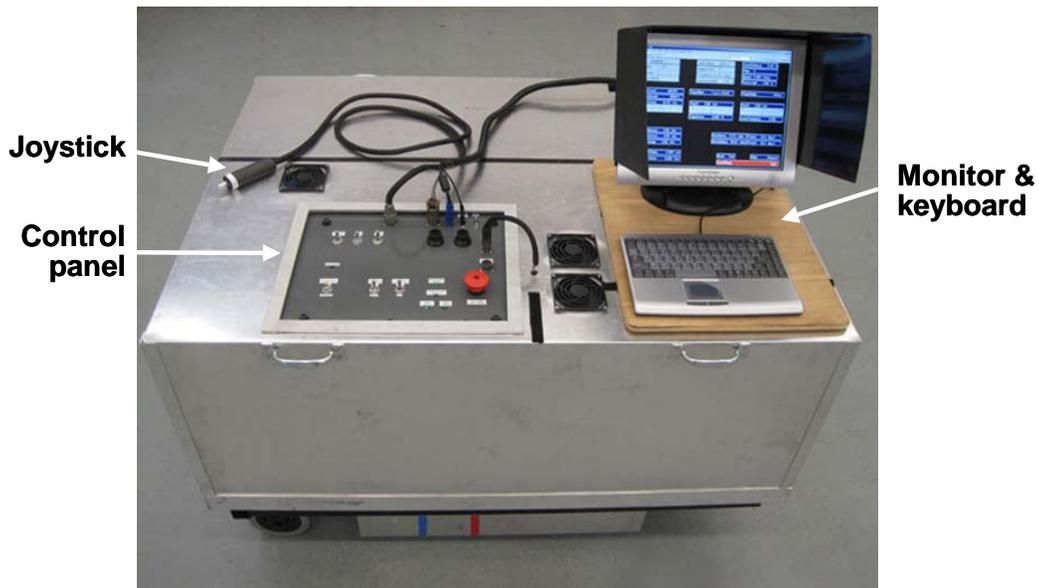
a. The benchmark profiler with its cover in place, viewed from the left side
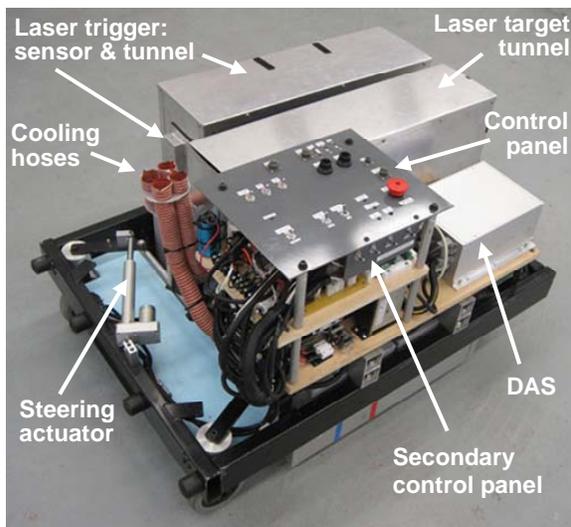
b. With the cover removed, from the left front
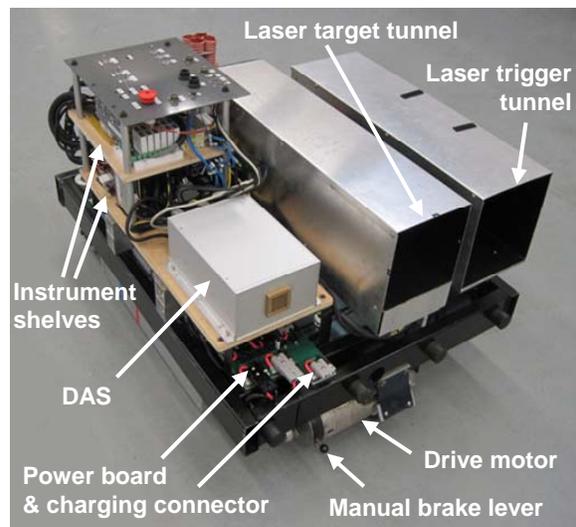
c. With the cover removed, from the left rear

Figure 2.1. Three views of the benchmark profiler showing the location of its controls and major components

- *The control panel*
- *The joystick*
- *The monitor & keyboard*
- *The manual brake lever*
- *The secondary control panel*

2.1.1. The Control Panel

The control panel, which is the top surface of the stack of shelves holding the electronic components (figure 2.1.b), is accessible through a "window" in the top of the cover (figure 2.1.a). A photo of the control panel with group indications added is shown in figure 2.2. The panel mounts nine connectors, six toggle switches, one palm switch, and five LED indicators.
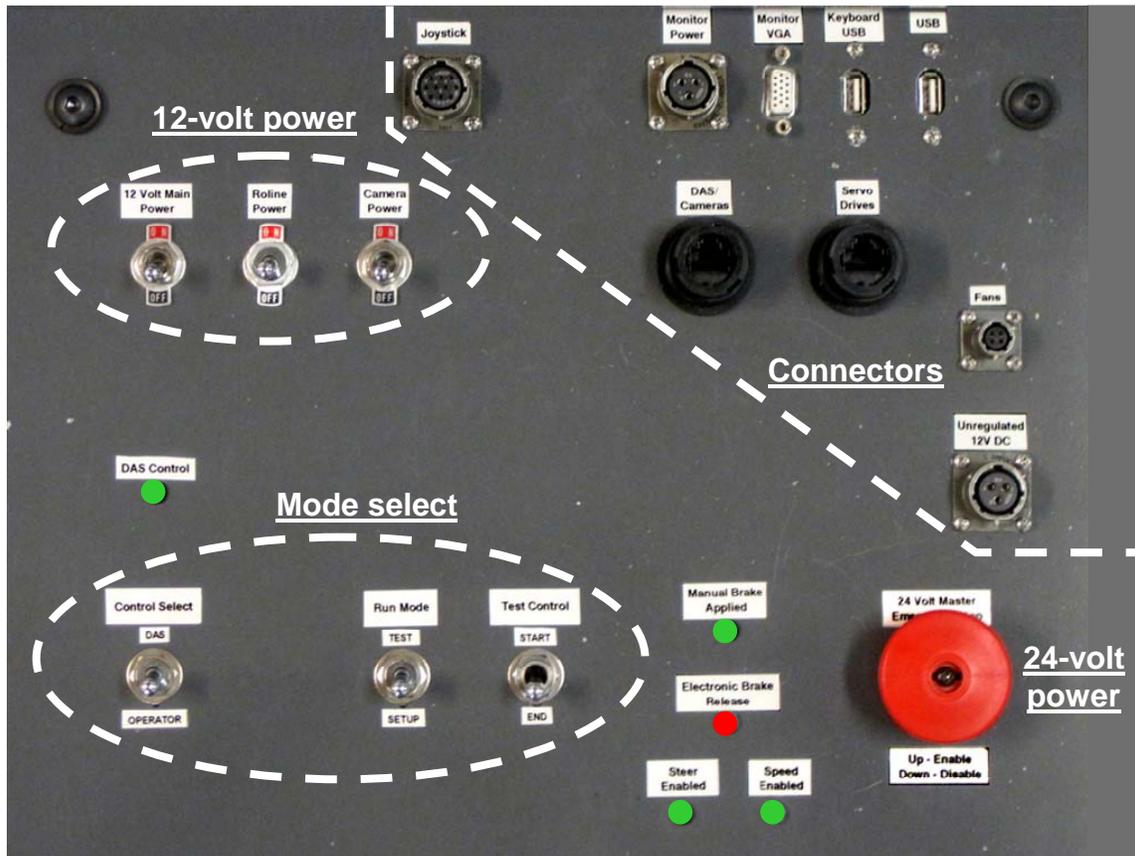
Figure 2.2. The benchmark profiler's control panel (with group indications added)

The functions of the connectors are as follows:
- *Joystick* — I/O for the joystick
- *Monitor Power, Monitor VGA, Keyboard USB, and USB* — I/O for the UMTRI DAS
- *DAS Cameras, Servo Drives* — I/O for the two Ethernet switches
- *Fans* — Power for the cooling fans
- *Unregulated 12V DC* — Misc. 12-volt power

The six toggle switches are arranged in two groups. Three switches are associated with the 12-volt, instrumentation system:

- The *12 -volt Main Power* switch controls power to the DAS, the Ethernet switch for the DAS and the cameras, and the 12-volt instrumentation system (instruments other than the drive-motor and steering-system encoders and the steering actuator's potentiometer).
- The *RoLine Power* switch controls power to the RoLine 1130, given that the main 12-volt power switch is on.
- The *Camera Power* switch controls power to the TargetCamera and the TapeCamera, given that the main 12-volt power switch is on. This switch also enables power to the light bar, which illuminates the filed of view of the TapeCamera, given that the 24-volt master switch is on.

Separate control of power to the RoLine and the cameras is required because these devices must be powered up in a specific sequence while booting the DAS and executing the profiler's control program (see section 2.3.1).

The other three toggle switches provide for selecting the mode of control:
- The *Control Select* switch selects between the *OPERATOR* mode for manual control by an operator using the joystick or *DAS* control.
  The *DAS Control* LED indicator above this switch illuminates (green) when the profiler is being controlled by the DAS.
- The *Run Mode* switch selects between the *SETUP* mode and the *TEST* mode when DAS control has been selected. In *SETUP*, steering is controlled by the TapeCamera tracking the guidance tape, while the operator controls forward and reverse motion using the joystick. In the *TEST* mode, the DAS controls speed as well as steering.
- The *Test Control* switch is used to initiate or to prematurely end a test. Transitioning this switch from the *END* to the *START* position initiates the test sequence under DAS control. Normally, the DAS ends the test automatically when the entire test sequence has been completed. (The operator must eventually put this switch back into the *END* position in order to initiate the next test.) However, the operator may end a test prematurely by throwing this switch to *END* before the test is completed.

The large red palm button at the lower right of the panel is the *24-Volt Master* switch for the steering and drive systems, the LED light bars that illuminate the field of view of the TapeCamera, and the Ethernet switch for the servo drive controllers. This switch also serves as the *Emergency Stop* panic button.

The four LED indicators to the left of the *24-Volt Master* switch indicate states of the steering and drive systems as follows:
- *Manual Brake Applied* — LED illuminates (green) when the manual brake lever is in the brake-applied position (down). (See section 2.2.4.)
- *Electric Brake Release* — LED illuminates (red) when electric brake-release override is activated by the drive-motor controller. (See section 2.2.4.)
- *Steer Enabled* — LED illuminates (green) when the steer-control servo system is operating normally. This LED is off if the controller is not powered or when a fault has been detected and the system has automatically been disabled.

- *Speed Enabled* — LED illuminates (green) when the speed-control servo system is operating normally. This LED is off if the controller is not powered or when a fault has been detected and the system has automatically been disabled.

2.1.2. The Joystick

The joystick control is on a six-foot cable that plugs into its connector on the control panel (figure 2.1.a). It provides for manual control of the steering and speed of the profiler with the usual joystick arrangement of left-right for steering and fore-aft for forward and reverse speed. Both systems respond proportionately to their respective input.

2.1.3. The Monitor and Keyboard

A monitor and keyboard connect to the UMTRI DAS computer via power, VGA and USB connectors on the control panel (figure 2.1.a). For outdoor use, the monitor is equipped with a removable sun shade. With connectors removed from the back of the monitor, the monitor can fold to a low-profile position.

With the profiler's control program running, inputs at the keyboard constitute control inputs for the automatic operation of the benchmark profiler. The monitor screen presents a display of multiple readouts of operating variables and the usual style of drop-down menu information.

2.1.4. The Manual Brake Lever

The manual brake lever is located at the left end of the drive motor at the rear of the profiler. With the lever in the up position, the mechanical friction brake in the drive unit is held in the released state mechanically. With the lever down, the brake is nominally applied, except that it may also be released by an electric command from the motor controller. The standard operating condition is for the brake lever to be down and, hence, the brake applied except when overridden by the electric release. The release command is activated when the joystick or the DAS provides a non-zero speed command, and the drive system is responding properly. However, if the drive servo error becomes excessive or other faults are detected, the speed command is set to zero and the brake is applied by disabling the release command.

2.1.5. The Secondary Control Panel

The secondary control panel is a small panel mounted to the underside of the control panel (figure 2.1.b). It is accessible only when the profiler's cover is off. It mounts four additional toggle switches that allow individual on/off control of the two cameras and individual run/abort control of the two servo control systems. The normal states for these four switches are the on and enable positions. The ability to turn off these four functions individually is for debug and maintenance purposes only.

2.2. Manual Operation

The benchmark profiler may be driven manually, under its own power, using the joystick to control steering and speed. This mode of operation requires only the 24-volt system to be switched

on. The 12-volt system may be either on or off, and, if on, the profiler control program may be running or not running on the DAS.

To drive the profiler manually:
- Place the manual brake lever in the down (applied) position.
- Insure that the joystick is properly plugged in at the control panel.
- Place the *Control Select* toggle switch (lower right on the control panel) in the *OPERATOR* position.
- Enable the 24-volt system (red, palm button up).
- Use the joystick to control both steering and speed of the profiler.

Upon first powering the 24-volt system, the two servo control cards require a few seconds to boot. The *Speed Enable* and *Steer Enable* indicators will illuminate when the boot-up is complete and the systems are ready to go. Also note that until the speed-control servo is fully booted, the *Electric Brake Release* indicator will illuminate even though the brake-release signal is not active. Once the controller is operating, the brake is released only when the speed command from the joystick is non-zero and no faults are identified by the controller. In the event that a fault is detected in one of the servo systems, that system will automatically be disabled and the associated LED *Enable* indicator will go out. In this case, turn the 24-volt system off and then back on to reboot both servo systems.[1]

The maximum speed under operator control is 2.5 ft./sec. (both forward and reverse), a slow-to-moderate walking speed. The minimum turning radius at the inside front wheel is about 150 in. and about 200 in. at the outside front corner of the cover.

The benchmark profiler may also be pushed "by hand." To push the profiler short distances, place the manual brake lever in the up (release) position, and push the profiler slowly, either forward or reverse. Pushing on the exposed black frame at the front or rear is preferred. Pushing on the cover with moderate force is acceptable. Pushing the profiler may be done with the 24-volt system on so that the profiler can be steered with the joystick. However, if the profiler is moved more than about 8 in., the speed-control system will go into a fault state and disable itself. This is not a problem, but it does require that the 24-volt system eventually be switched off and then back on to reboot the servo controllers.

Drive plate
machine screws

Figure 2.3. A sketch of the right side of the drive wheel

If it becomes necessary to move the profiler by hand for substantial distances (i.e., more than just a few feet), the drive wheel should be released from the motor shaft by removing the two drive-plate machine screws indicated in figure 2.3. With these screws removed, the rear wheel turns freely on its axle without rotating the motor shaft. In this condition, the motor encoder does not rotate and the drive controller will not sense a fault.

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[1] The most common fault that results in disabling a controller is a large servo error in the drive system resulting from the inability of the drive motor to overcome a relatively large resistance to motion. Such events are more common when voltage supplied by the motor batteries is low.

When reinstalling the drive-plate screws, start them in their holes with a few turns, turn the wheel to seat the screws firmly in the drive-plate slots, and then tighten the screws firmly.

2.3. The DAS Control System

Profile measurements are always made with the benchmark profiler being controlled automatically by the DAS computer. The program that controls the benchmark profiler is called *Cart*. There is a shortcut icon for *Cart.exe* on the DAS Windows desktop.

Shortcut icons for three other programs also appear on the desktop. *InSight-Explorer* provides access to the two machine-vision cameras. *DMC Smart Terminal* is for accessing the servo controllers. The program *kClient* is for dealing directly with the RoLine 1130. These three programs are provided for maintenance and debug only; none of these programs are required for conducting profile measurements.

When operating the benchmark profiler under control of the DAS, no program other than *Cart* should be running. *Cart* is a real-time control program and may not function reliably if other executable programs are running and placing demands on the operating system.

In the normal testing situation, the 12-volt system would be turned on, the DAS booted, and the *Cart* program executed at the start of the testing session. Several general test and data-logging parameters for the session would be entered via the keyboard using menu options. Immediately prior to measuring each individual road segment, the profiler is maneuvered into the proper initial position using a combination of the *OPERATOR* and *DAS/Setup* control modes, and a few run-specific parameters are entered. The control panel switches are used to select the proper operating modes and to signal the initiation of the actual test.

Of course, the 24-volt system must be turned on to maneuver the profiler and conduct tests under DAS control. However, to save battery power during a test day, the 24-volt system may be turned on or off, as circumstances suggest, without regard to the state of the 12-volt system.

The remainder of this section describes the details of booting the 12-volt system, initiating the control program, entering the various control parameters and executing the test. The details of the operation of the ground-based spinning laser are presented in section 3, and the broader view of the entire test procedure, and all its individual steps, is presented in section 4.

2.3.1. Booting the System and Initiating the Control Program

Booting up the entire test and instrumentation system, including the initiation of the control program, requires several steps to be taken in a very specific order. Before booting the system, the manual brake lever should be in the down (applied) position and the *Control Select* toggle switch should be in the *OPERATOR* position. Then the system may be booted in the following manner:

1. Switch on the main 12-volt power and wait for the DAS to boot. Switching on the main 12-volt power immediately powers the DAS. Wait for the DAS to boot as indicated by the appearance of the standard, Windows-XP desktop on the monitor.

2. Switch on the RoLine power and wait for the RoLine to boot. The booting process of the RoLine, including the establishment of its Ethernet communication with the DAS, requires about half a minute. During this process, a pop-up window presenting a "Local Area Connection" message will appear on two separate occasions (figure 2.4). Once the second notice has appeared, the control program may be executed.

3. Execute the profiler control program by double clicking the shortcut icon for *Cart.exe* on the desktop.

4. Switch on the camera power. This may be done immediately after initiating the control program; the cameras may boot and establish their Ethernet communications as the program is initiating.
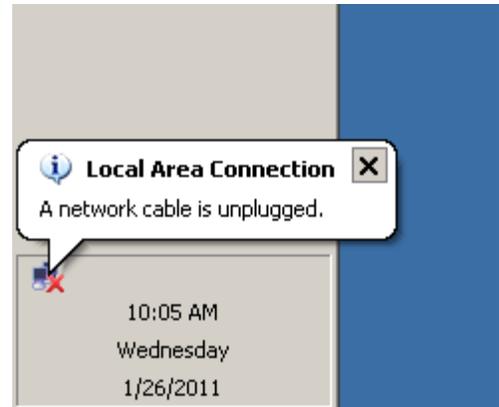
Figure 2.4. A "Local Area Connection" message appears twice while the RoLine is booting

In the event it becomes necessary to shut down the *Cart* program, the camera power must also be switched off so that, in restarting *Cart*, steps 3 and 4 may be repeated properly. If it becomes necessary to reboot the entire system, the cameras and the RoLine power must be switched off and all four steps repeated in order.

2.3.2. The Main Display Screen

When the control program is up and running its *Main* screen will appear on the monitor as shown in figure 2.5. This screen displays thirty-five "gauges" that present various parameters and operating variables grouped by data type.

The test-ID and test-parameter data groups are shown with a gray background to indicate that they present static, parametric values, that is, values which are entered by the operator and do not vary during a test. Entry of these data is discussed in section 2.3.3.

All the other data fields on the screen are active data readouts that vary over time during a test. Tables 2.1 and 2.2 review each of the display fields. Tables 2.3 through 2.5 present enumerations of the various *states* and *statuses*.

Four *related responses* are located directly to the right of the four test parameters. Each individual response gauge is related to the static parameter to its left. See table 2.2.

Fields associated with the RoLine and the two cameras occupy the center of the screen (vertically). The current operational *status* and the outputs of primary concern for test control and monitoring are presented (see table 2.2 and 2.3).
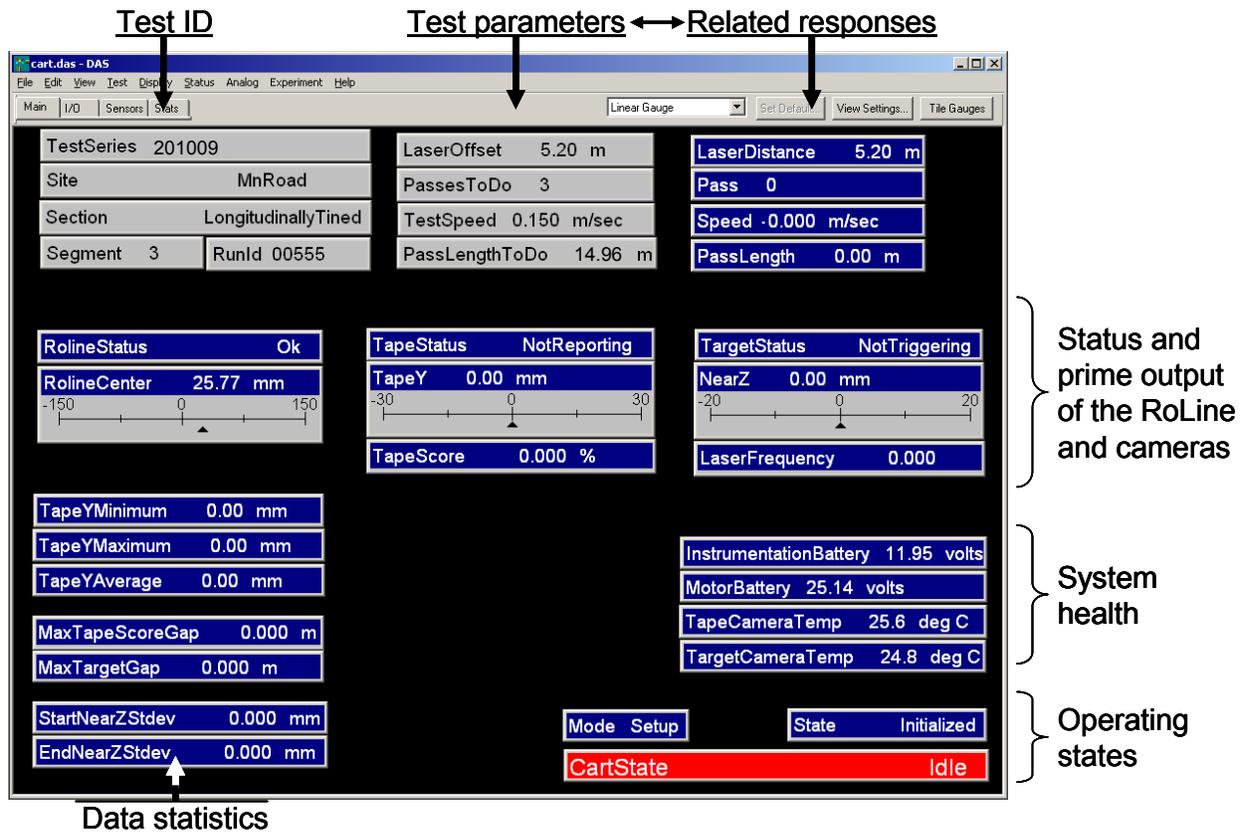
Figure 2.5. The main display screen is organized in groups by data type

Table 2.1. Static data fields of the main display screen

Group	Field	Definition	Input dialog*
Test ID	TestSeries	ID number of the test series	Edit Header
	Site	ID of the test site	Edit Header
	Section	ID of the road section being profiled	Edit Header
	Segment	Number of the segment being profiled	Edit Header
	RunID	Index number for data files for this run	Edit Header
Test parameters	LaserOffset	Initial distance from the spinning laser to the near laser screens; 5.2 m. (17 ft.) standard (see figure 2.7)	Edit Parameters
	PassesToDo	Number of repeat measurement passes over segment; 3 passes standard	Edit Parameters
	TestSpeed	Profiler speed (forward and reverse) during measurement; 0.15 m./sec. standard	Edit Parameters
	PassLengthToDo	The distance to be traveled by the profiler in one measurement pass; 14.94 m. standard (see figure 2.9)	Edit Header

* The *Edit Header* and *Edit Parameters* dialog boxes are selected under the *Test* menu. The *Edit Header* dialog also appears when *New* is selected under the *Test* menu.

Table 2.2. Active data fields of the main display screen

Group	Field	Definition and comment	Typical range during test or safe max/min values
Related responses	LaserDistance	Distance from the spinning laser to the near laser screens	5 to 25 m.
	Pass	The index number of the current measurement pass	0 to PassesToDo
	Speed	The profiler's current speed; forward motion positive, reverse motion negative	TestSpeed ± 0.1 m./sec.
	PassLength	The distance traveled so far during the current pass	0 to PassLengthToDo m.
RoLine	RoLineStatus	The current status of the RoLine	See table 2.3
	RoLineCenter	The current RoLine measurement of the road profile at the center point of the RoLine's sweep	14 to 34 mm. (23.7 mm. on a smooth surface)
TapeCamera	TapeStatus	The current status of the TapeCamera	See table 2.3
	TapeY	The lateral displacement of the guidance tape in the TapeCamera's field of view	± 11 mm. max and min
	TapeScore	The quality of the match between the TapeCamera's current image of the guidance tape and the camera's search pattern image of the guidance tape	Hi range: 95 to 100 % Low range: 85 to 95 %
TargetCamera	TargetState	The current status of the TargetCamera	See table 2.3
	NearZ	The vertical position of the spinning laser beam in the TargetCamera's field of view	± 75 mm.
	LaserFrequency	The frequency of the spinning laser rotation as sensed by the laser trigger	17.7 Hz. ± 0.5 Hz.
System Health	InstrumentBattery	The current voltage supplied by the instrument batteries	11.5 volts minimum
	MotorBattery	The current voltage supplied by the motor batteries	23 volts minimum
	TapeCameraTemp	Air temperature immediately adjacent to the TapeCamera	0º C. min; 40º C. max
	TargetCameraTemp	Air temperature immediately adjacent to the TargetCamera	0º C. min; 40º C. max
Operating states	Mode	Run mode under DAS control; set by Run Mode switch on control panel	Test or Setup
	State	State of the test (data collection) currently executing	See table 2.5
	CartState	State of the profiler control algorithm	See table 2.4
Measurement statistics	TapeYMinimum	Minimum value of TapeY during the current test	-11 mm. minimum
	TapeYMaximum	Maximum value of TapeY during the current test	11 mm. maximum
	TapeYAverage	Average value of TapeY during the current test	± 6 mm
	MaxTapeScoreGap	The maximum distance traveled during the test without receiving TapeCamera data	0.15 m. maximum
	MaxTargetGap	The maximum distance traveled during the test without receiving TargetCamera data	0.03 m. maximum
	StartNearZStdev	The standard deviation of NearZ during the most recent StartDwell	0.25 mm. maximum
	EndNearZStdev	The standard deviation of NearZ calculated during the most recent EndDwell	0.25 mm. maximum

Table 2.3. Enumerations of the RoLine and camera status variables

Device	Status	Definition and comment
RoLine	NoSync	Synchronization pulse not received from RoLine. Uncommon; indicates fault.
	NotReporting	Data packet not received from RoLine. Uncommon; indicates fault.
	OK	RoLine data being received properly.
Cameras	Offline	Camera offline. Common when starting *Cart.exe* and booting cameras. Otherwise indicates fault.
	NotTriggering	Camera not triggering. Common for TargetCamera when not testing and spinning laser beam not sensed by laser trigger. Uncommon for TapeCamera. Indicates fault during testing.
	NotSending	DAS not sending data packets to camera. Uncommon; indicates fault.
	NotReporting	Data packets not received from camera. Common when not testing if laser-beam image not found by TargetCamera or guidance-tape image not found by TapeCamera. Rare but occasional during testing. Indicates fault if sustained during testing.
	OK	Camera data being received properly.

There are four gauges monitoring *system health* on the right of the screen below center. Two gauges monitor air temperatures immediately adjacent to the two cameras, respectively. The camera specifications limit ambient temperature to the range of 0º to 40 º C. The other two health gauges monitor the battery voltage supplied to the instrumentation system (nominally a 12-volt system) and the drive and steering systems (nominally a 24-volt system). The recommended minimums are, respectively, 11.5 and 23 volts. Operating below 11.5 volts may result in drop out of one or more instruments. Drive system performance degrades noticeably if supply voltage falls below 23 volts.

Three gauges that monitor the operating state of the profiler are grouped in the lower right of the screen. The *Mode* gauge indicates the DAS control mode selected with the *Run Mode* toggle switch: *SetUp* or *Test*. The *CartState* gauge shows the current operational state of the profiler in relation to its operational control by the DAS. There are sixteen cart states; they are reviewed in table 2.4. Cart states generally proceed in the sequences shown in the table except as noted there. The *State* gauge presents the current state of the data collection process within a test run. There are a total of six data-collection states in the UMTRI DAS system, but only three are applicable to the benchmark profiler. These three are reviewed in table 2.5.

Seven gauges are grouped in the lower left of the main screen. They present seven statistical measures of data collected during the current test or the most recent pass.

The maximum, minimum, and average values of *TapeY* are presented in order that the performance of the automatic steering system can be monitored during the test. The value for *TapeY* as the profiler tracks a straight guidance tape on a smooth, flat surface can be expected to remain more-or-less in the ±1 mm. range. When backing, this variance can be expected to increase quite a bit to about ±3 or 4 mm. On a test section, the average value of *TapeY* will be influence by the cross slope of the test surface. The variance of *TapeY* will be influenced by surface roughness and by the straightness (rather, lack of straightness) of the guidance tape, especially when backing. If and when *TapeY* is outside the range of ±11 mm, the RoLine sweep will be improperly aligned with respect to the section of the surface intended for measurement. A range of ±8 mm is preferred for data analysis.

Table 2.4. Enumerations of the CartState variable

CartState	Operating condition and comments
0. Start	*Cart.exe* program booting. Never seen by operator.
1. Idle	CartState when profiler is under *Operator* control. Brief, initial condition in control sequencing under *DAS* control.
2. CameraChecks	In *SetUp Run Mode*: check TapeCamera; jump to 4, then 13 when checks passed. In *Test Run Mode*: check both cameras; continue sequence when checks passed.
3. RoLineChecks	Checking RoLine.
4. WaitForBrake	Waiting for manual brake lever to be put into apply (down) position.
5. WaitForRunning	Waiting for a new test to be initiated by executing the *New* and *Start* commands in the *Test* menu.
6. WaitForStart-Switch	Waiting for the *Test Control* toggle switch to transition from *End* to *Start*. Data collection and speed sequencing initiated when switch is thrown.
7. StartDwell	Speed command is zero for StartDwell period.
8. EnableServos	Send enable signal to servo controllers; pause. Brief, may not be noticed by operator.
9. RampingUp	Command ±TestSpeed (odd- or even-numbered pass; observe profiler speed transitioning from zero to ±TestSpeed. Brief; may not be noticed by operator.
10. AtSpeed	±TestSpeed obtained; proceed for the length of the pass.
11. RampingDown	Command zero speed; observe profiler speed transitioning from ±TestSpeed to zero. Brief; may not be noticed by operator.
12. StopDwell	Speed command is zero for StopDwell period. If there is another pass to do, jump to 7. If done, jump to 15.
13. SetupWait	Send enable signal to servo controllers; pause. Brief, may not be noticed by operator.
14. Setup	Operate in *Setup Run Mode*: Steer commanded from TapeCamera; speed command from joystick. Check *Run Mode* switch; if *Test*, jump to 1.
15. AllDone	Stop data collection; manage data files. Brief, then jump to 1.

Table 2.5. Enumerations of the State variable applicable to operation of the benchmark profile

State	Operating condition and comments
0. Stopped	Data collection complete. All data files flushed to disk
2. Running	Data collection in progress if enabled by CartState.
3. Initialized	Data files initialized. Waiting for start command.

MaxTapeScoreGap and *MaxTargetGap* provide a means to monitor whether the two cameras have returned data consistently at an adequate frequency. The TapeCamera operates asynchronously, but at more-or-less 10 Hz. At 0.15 m/sec. this implies a normal TapeScore gap of about 0.015 m. TapeCamera data is intended to accurately mark longitudinal position once per foot of travel. To prevent successive loss of more than one such mark, the maximum allowable TapeScoreGap is 0.15 m. (0.5 ft). Nominally, the TargetCamera should return data following each sweep of the laser beam. At approximately 18 Hz. and with the standard *Speed* of 0.15 m./sec., the expected TargetGap is about 0.008 m. Missing more than two consecutive sweeps of the laser (MaxTargetGap > 0.03 m.) renders the associated pass invalid.

The measures of the standard deviation of *NearZ* during the start and dwell periods provide a means to monitor the stability of the spinning laser beam, particularly as it is influenced by environmental conditions such as wind, dust or moisture in the air, and "heat waves" above a warm road surface. The more important of these, of course, are the dwell periods occurring farthest from

the laser, i.e., EndDwell for odd-numbered passes and StartDwell for even-numbered passes. Assuming a standard 3-pass measurement, these can be read simultaneously anytime during the reverse motion of pass number 2 and after the completion of pass 3. A value greater than 0.25 mm. typically corresponds to atmospheric conditions that reduce repeatability below a critical level. In this instance, the user should select shorter segments or wait for more favorable conditions. When the value is near the borderline (i.e., near, but not above 0.25 mm.), the user should opt to increase the number of passes per segment to 5.

2.3.3. Entering Test-Control Parameters and Test-ID Data

Test parameters and ID data are entered using the *Edit Parameters* and *Edit Header* dialogs, which are accessed via the *Test* menu.

Nineteen parameters that describe and/or control the automatic operation of the benchmark profiler are displayed and edited using the *Edit Parameters* dialog. This dialog is shown in figure 2.6 with all the parameters displayed with their standard values.
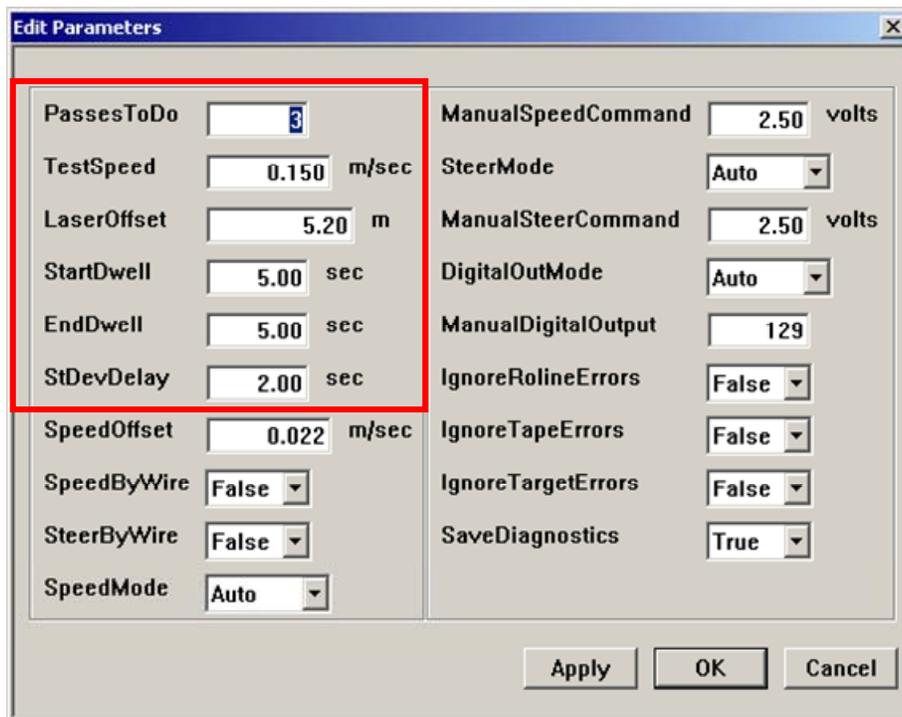
**Figure 2.6. The *Edit Parameters* dialog with standard values shown
and the five parameters subject to change highlighted**

Of these nineteen parameters, only the first six serve to help define the conduct of a test run and are therefore subject to change by the operator during a test program. The other thirteen parameters relate to basic operating properties of the automatic system and should not be altered by a test operator (except when gathering level reference data as described in section 5.1). They are available primarily for diagnostic purposes. These thirteen parameters are automatically set to their standard values when the *Cart* program is booted. The first six parameters retain their most recent value when the program boots.

The six parameters related to a test run are the first six in the left-hand column of the dialog. The *standard values* of these parameters are shown in figure 2.6. They should only be changed from these standard values on rare occasions for specific purposes. The five parameters are as follows:

- *PassesToDo* — the number of passes that are to be made over the road segment to be measured, i.e., the number of repeats of the measurement.
  The standard value of *PassesToDo* is 3. Odd-number passes (e.g., 1 and 3) are done with the profiler moving forward from the start to the end of the segment. Even-number passes (e.g., 2) are done with the profiler in reverse, returning from the end of the segment back to the start. In order to finish the measurement of a segment at its end, in a convenient position to begin the next segment, it is always desirable to do an odd number of passes. Under some circumstances it may be appropriate to undertake 5 passes. Occasionally, if there was a problem with a previous test run, it may be appropriate to repeat just one or two passes.

- *TestSpeed* — The commanded speed of the profiler, in both forward and reverse, while profiling.
  The standard value is 0.15 m./sec. Critical, spatial data-collection rates are based on this value. The automated data reduction calculations *require* that the command speed be this standard value. Only on rare occasions might it be appropriate to set a *TestSpeed* to a value other than 0.15 m./sec.

- *LaserOffset* — the distance from the spinning laser to the laser target screen on the profiler at the outset of the test run.
  The *LaserOffset* for the standard test setup is 5.2 m. The standard *LaserOffset* is illustrated in figure 2.7. Details of the standard test setup are given in sections 4.5 and 4.6. A test should never be set up with a *LaserOffset* of less than 5.2 m.
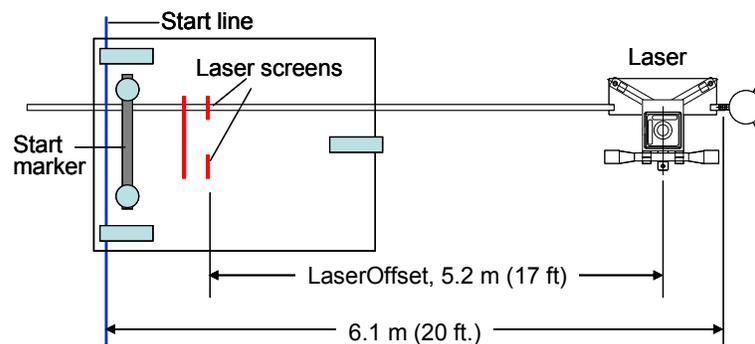
Figure 2.7. The initial laser offset for the standard test setup is 5.2 m.

- *StartDwell* and *EndDwell* — time periods at the beginning and end of each measurement pass, respectively, during which the DAS collects data while the profiler is stationary.
  The standard times for the *StartDwell* and the *EndDwell* are both 5 seconds. As noted in section 2.3.2, the primary purpose is to monitor the stability of the spinning laser beam.

- *StDevDelay*. Standard deviations of the *NearZ* signal are calculated during the StartDwell and EndDwell periods after a time delay of *StDevDelay*. For example, using the standard values shown in figure 2.6, *StartNearZStDev* and *EndNearZStDev* would be calculated during the final 3 seconds of the 5-second *StartDwell* and *EndDwell*, respectively.

The second dialog used to enter test parameters is the *Edit Header* dialog, which is shown in figure 2.8. This dialog presents five parameters. All of these parameters are saved with the data files from the test run.

This dialog is accessible under the *Test* menu by selecting *Edit Header...*. For convenience when conducting tests, this dialog also appears when a new test run is initiated by selecting *New...* under the *Test* menu. See the discussion of the *RunID* number, below.
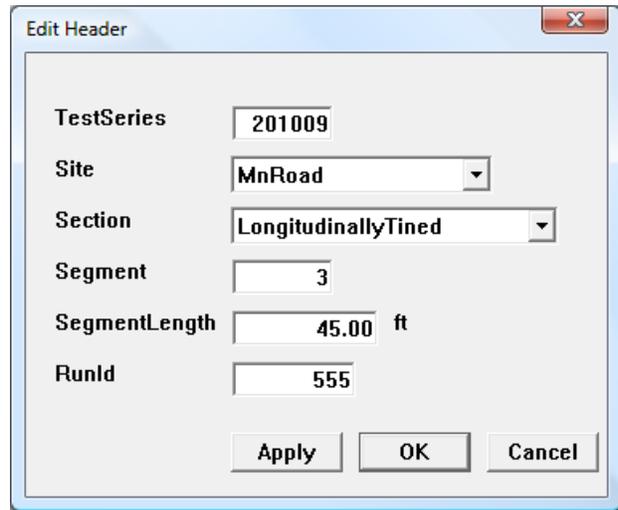
Figure 2.8. The *Edit Header* dialog

The first parameter in this dialog is the (integer) ID number of the test series. In the example of figure 2.8, the *TestSeries* parameter has been assigned a number to indicate the year (2010) and month (09) of the test series. The primary purpose of this parameter is to properly associate data from the benchmark profiler with the appropriate rod-and-level survey data.

The next two parameters of the dialog are the name of the general test *Site* and the name of the road *Section* to be profiled. Both of these are selected from their drop-down menus.

The road *Section* to be profiled may be several hundred feet long, but profile measurements are made in *segments* that are typically just 45 ft. long. The third parameter in this dialog is the (integer) number of the *Segment* which is to be measured.

The next parameter is *SegmentLength*, the actual length of the segment to be profiled. Since the units of the guidance tape are feet, and for the convenience of the field operators, *SegmentLength* is entered in feet. The standard *SegmentLength* is 45 ft.

In order to be able to precisely align the profile data from one segment to the next, start and end markers are placed on the road surface 0.50 ft. before and after the segment start and end lines, respectively. In addition, 1.5 ft. are added to both the beginning and end of the measurement of a segment to insure that start and end markers are clearly visible in the data. (See sections 4.5 and 4.6 for additional details.) Hence, as shown in figure 2.9, the total distance to be traveled by the profiler is 4 ft. (1.22 m.) more than the length of the segment to be measured. This total distance traveled, in meters, is *PassLengthToDo* (see figure 2.5 and table 2.1).

PassLengthToDo is calculated by the *Cart* program as follows:

$$PassLengthToDo = 0.3048 * SegmentLength + 1.22 \quad m.$$

The last parameter in this dialog is the *RunID* number. It is typically not necessary for the operator to enter the *RunID* number: When a new test is initiated by selecting *New...* under the *Test* menu, the *RunID* number is automatically incremented from its previous value, and the *Edit Header* dialog is opened for review by the operator. (When the *Edit Header* dialog is opened by selecting *New...*, the only option available for closing the dialog and proceeding is the *OK* button.)
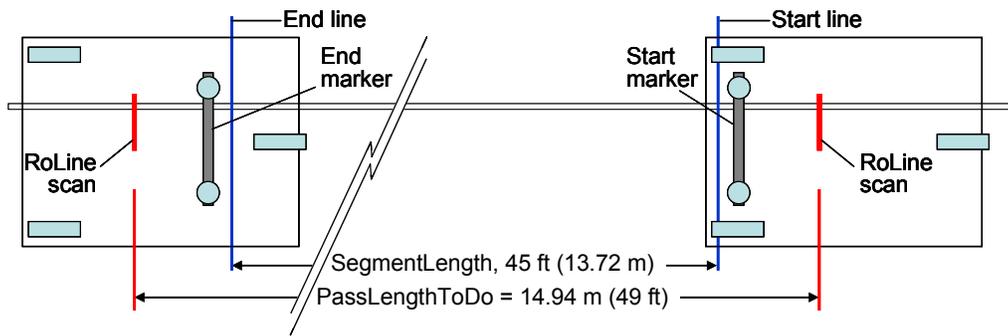
Figure 2.9. The segment length and pass length for the standard-length test segment

Occasionally, however, entering the *RunID* numbe by hand may be appropriate. In so doing, however, one should insure that this will not create a conflict with the *RunID* number of any data files that already exist.

2.4. Conducting a Test Run

The broad description of the conduct of a test program is covered in section 4. This includes general preparation of the sight, layout of the guidance tape, and placement of the ground-based spinning laser. Section 4.6 describes the procedures for the immediate conduct of the profile measurements and is very closely related to this section (2.4), which is intended to present only the "mechanics" of operating the profiler immediately prior to and during the conduct of a profiling test run.

All three operational states are used during the test process, these being:
- *OPERATOR* control;
- *DAS* control, *SETUP* mode;
- *DAS* control, *TEST* mode.

The manual brake lever must be in the applied (down) position for operation in any of these three states. The brake is released by the electric brake release whenever the drive-motor controller receives a non-zero speed command from the joystick or the DAS and no fault is detected.

At the outset, we assume that the road section is fully prepared, the guidance tape is laid out, the spinning laser is setup, the start- and end-marker plates are properly positioned, and that the benchmark profiler is fully activated and in the near vicinity of the start of the guidance tape.

2.4.1. Position the Profiler Over the Guidance Tape

The initial step of positioning the profiler over the guidance tape is typically required only when preparing to profile the first segment of a new tape layout. The profiler will already be located over the tape when preparing to measure subsequent segments of the same tape layout. (See section 4.6.3.)

In the *OPERATOR* control mode, use the joystick to position the profiler between the spinning laser and the start-line marker and sufficiently well located over the guidance tape to enable DAS-control of steering. The black lines on the front and rear face and across the top of the profiler cover are provided to aid in this process (see figure 2.10). In general, this initial alignment is sufficiently

a. View of the profiler and tape from the front   **b. View of the profiler and tape from the rear**
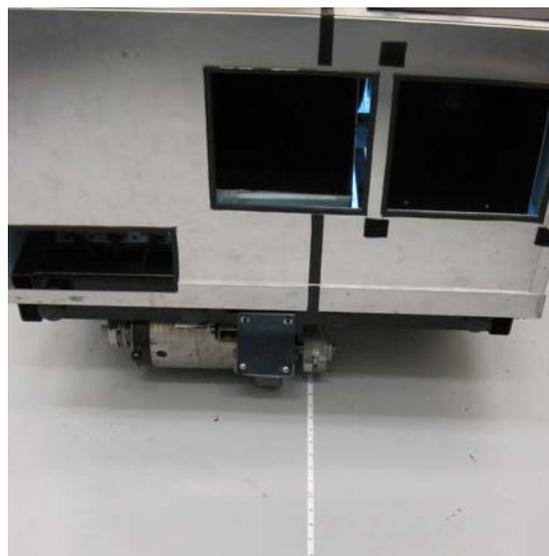
Figure 2.10. The benchmark profiler positioned in good alignment with the guidance tape

accurate as soon as the *TapeStatus* gauge on the monitor screen reports *OK*. It is desirable, however, for the *TapeY* gauge to report a value within the range of ±15 mm.

It is often easiest to perform this maneuver while standing directly in front of the profiler. It is best to perform this maneuver close to the zero-end of the alignment tape in order that there are several feet available to move forward toward the start line.

2.4.2. Position the Profiler for the Start of the Measurement

Switch the *Control Select* and *Run Mode* toggle switches to select the *SETUP* mode under DAS control. In this mode, the TapeCamera and DAS control steering while the operator controls speed using the joystick. Move the profiler forward slowly. Within 3 or 4 feet of travel the *TapeY* gauge should transition to a quite small value. Continue to drive the profiler forward slowly until the centerline of the front wheels is well aligned with the start-line marker strip (figures 2.11 and 2.9). Check the *TapeY* reading to insure that the profiler is well aligned laterally. The profiler is now in position to start a new test run. This positioning of the profiler locates the spinning laser target approximately 17 ft. (5.2 m.) from the spinning laser at the start of the measurement of the segment. It also insures that the data record will include RoLine scans of both the start- and end-marker plates.

Figure 2.11. The benchmark profiler in position to start the measurement of a segment

2.4.3. Initialize and Execute a Test Run

To initialize and execute a new test run, follow these steps:

- Select *DAS* control, *TEST* mode. Leave the *Control Select* in the *DAS* position and switch the *Run Mode* toggle switch to select the *TEST* mode. In this mode of operation, the TapeCamera and DAS control both steering and speed of the profiler.
- Confirm the test-control parameters. Select *Edit Parameters...* under the *Test* menu and confirm that all the parameters shown in the dialog are as intended. (This discussion assumes that all these parameters have standard values as shown in figure 2.6.) Close the dialog.
- Confirm the proper *CartState*. At this point, the *CartState* should read "WaitForRunning."
- Initialize a new test run. Select *New...* under the *Test* menu. The *Edit Header* dialog will appear. Confirm that the five parameters in this dialog are as intended. Recall that selecting *New...* has already caused the *RunID* number to be incremented one digit from the most recent data set saved. If the *Site* and *Segment* names have already been selected, the only parameter in this dialog that the operator must update regularly is the *Segment* number. Click *OK* to close the dialog.
- Start the test-control sequence. Select *Start* from the *Test* menu. This will trigger the test control sequence as outlined in table 2.4 and the related discussion in section 2.3.2.
- Confirm the proper *CartState*. At this point, the *CartState* should read "WaitForStartSwitch."
- Start the test. Switch the *Test Control* toggle switch from *END* to *START*. (If this switch was left in the *START* position, just switch to *END* and then back to *START*.) The measurement sequence will now proceed automatically. The profiler will collect data while stationary for the initial *StartDwell* period, then collect data will moving forward along the segment at *TestSpeed* for a distance of *PassLengthToDo*, come to a stop and collect data for the *EndDwell* period. Assuming *PassesToDo* has been set to 3, this process will then be repeated two more times, except that the profiler will move in reverse, back to its initial position, during pass 2, and then forward again to the end of the segment during pass 3.
- Monitor the data statistics. Confirm that the data statistics shown on the monitor screen are within acceptable bounds. Note that the standard deviations for *NearZ* are updated for each dwell period. Hence, they should be checked when the profiler is at the far position after the start of pass 2, and again after pass 3.
- End the test. The test cycle ends automatically when the final *EndDwell* is complete and the *CartState* briefly reads "AllDone" and then quickly changes to "WaitForRunning." At this time, the *Test Control* switch should be switched to the *END* position. Note also that the test can be ended prematurely at any time by using this switch.

2.5. Shutting Down the DAS and Instrument System

The *Cart* program is shut down in the standard Windows fashion by clicking the **X** in the upper right corner of the program window.

To shut down the DAS and instrument system, first turn off the power for the RoLine and for the cameras. Then shut down the Windows operating system in the usual fashion using the Windows

Start menu or the CTRL-ALT-DELETE dialog. After Windows shuts down, "No signal received" will appear on the monitor screen. It is now safe to shut off the main 12-volt power.

3. ASSEMBLY AND OPERATION OF THE SPINNING LASER

This section identifies the components of the spinning-laser system that is used with the benchmark profiler and describes the procedures for their assembly and use.

3.1. Components

The central component of the spinning laser assembly is a modified Hamar L-740 Ultra-Precision Leveling laser. This devise is fitted with a multipurpose fixture that shrouds the laser, limiting its field of projection, and incorporates a sighting scope and the circuitry for regulating power supplied to the L-740. The laser with its shroud is mounted on a special tripod stand. The system also includes a rechargeable battery pack, with charger, that is capable of powering the system for well in excess of 24 hours of operation.

Figure 3.1. The spinning laser assembly, with battery pack, positioned over the guidance tape with the tripod alignment plate

| **a. The modified Hamar L-740** | **b. The laser shroud with sighting scope** | **c. The tripod base** |

Figure 3.2. The primary components of the spinning laser assembly

3.1.1. The Hamar L-740 Laser

The HAMAR L-740 <http://www.HamarLaser.com/systems/L740/> is a precision spinning laser primarily designed to provide a very accurate, horizontal reference plane in a large workshop environment (e.g., in the assembly hall for large commercial aircraft). The L-740 of the benchmark

profiler system has been modified in two significant ways relative to the standard model. (1) It is equipped (by HAMAR) with a 3-mW laser, which is more powerful than its standard laser. (2) UMTRI has replaced the standard 9-volt power receptacle with a cable that, along with additional circuitry and external battery pack, provides, respectively, regulated 9-volt power for the laser and bubble-level illuminators and modulated DC power for servo-control of the laser's rotational speed (approximately 18 Hz.).

Figure 3.3 shows a sketch of the modified L-740. The view presented is of the control-panel side that, in the benchmark profiler application, is the rear side. That is, in the sketch, one is looking "forward" in the direction of travel of the profiler. The sketch shows the units magnetic base that allows for mounting on any nominally horizontal, ferrous surface. Also shown are the six mechanical adjustment knobs, one course and one fine for yaw, pitch and roll, respectively. Of the three power switches, the switch for the spin motor (labeled "SCAN")has been disabled and is replaced by a switch on the shroud assembly (figure 3.4.c); the switch for the main power to the laser beam and the switch for the LEDs that illuminate the bubble levels remain operational. The speed control knob of the standard unit has also been disabled. Although not shown in the sketch, there are two precision bubble levels on the top surface of the laser: one for roll and one for pitch (figure 3.9). When used for benchmark profiling, the L-740 is leveled in roll, but pitch is determined by the overall slope of the road surface and is adjusted using the sighting scope.
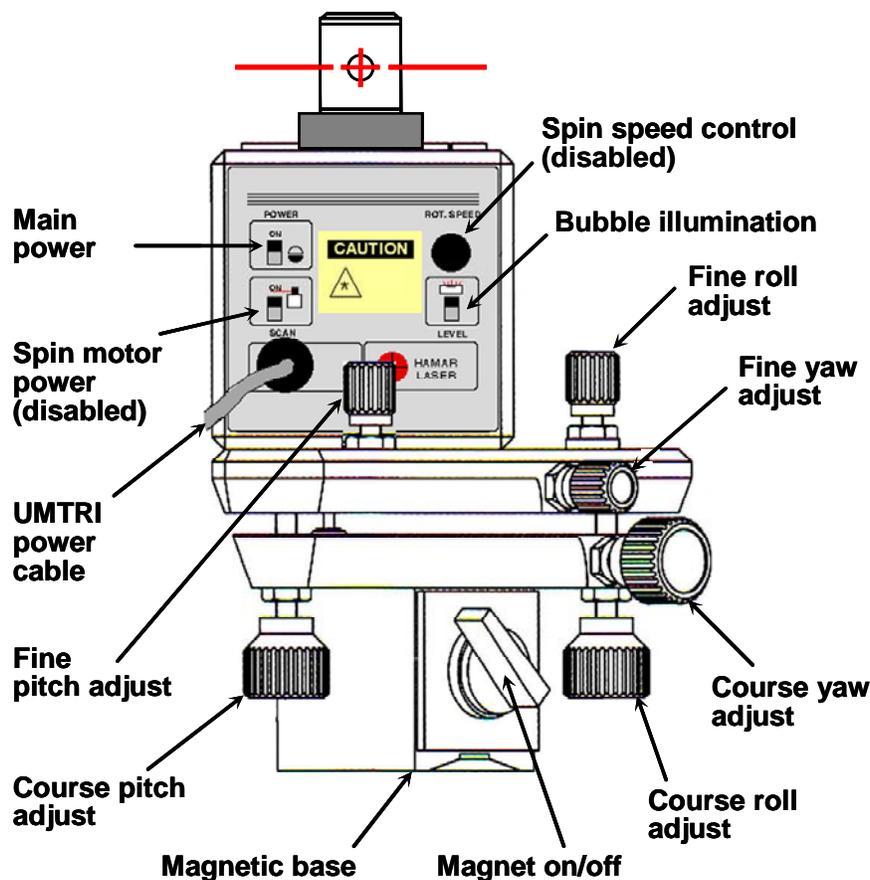
Figure 3.3. A sketch of the modified HAMAR L-740 spinning laser (rear view)

3.1.2. The Laser Shroud

The laser shroud is an aluminum housing that mounts on top of the L-740 and provides three functions:

- The shroud limits the long-range projection of the spinning laser beam to a small field of approximately 10 degrees centered along the path of the benchmark profiler.
- The shroud mounts a sighting scope used in aligning the L-740 in pitch and in yaw.
- The shroud houses the circuitry that provides regulated 9-volt DC power to the L-740 for the laser beam and the LEDs that illuminate the precision levels, and modulated DC power to the spin motor for closed-loop servo control of the spin rate (approximately 18 Hz.).

Figure 3.4 provides five views of the laser shroud assembly. Figure 3.4.a presents a rear view showing the laser beam as it sweeps past the primary window of the shroud that aims the laser along the path of the profiler in a "fan" of approximately 10 degrees. It can also be seen in this figure, that

a. Rear view showing the laser beam sweeping across the primary window

b. Rear quarter view showing the laser beam sweeping across the window into the circuit camber
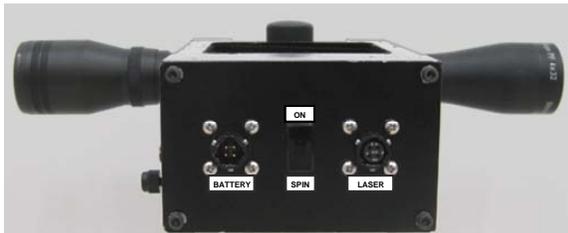
c. Side view: the cover of the circuit chamber
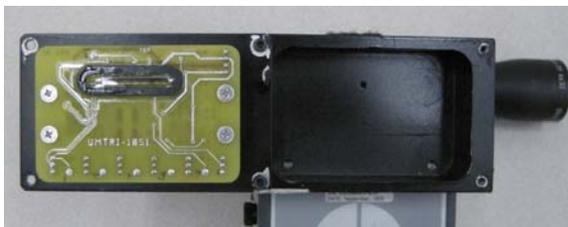
d. Side view with the circuit camber open and the laser-beam window and the photo diode visible

e. Bottom view showing the L-740 receptacle and the securing screws

Figure 3.4. Five views of the laser shroud assembly

the spotting scope is carefully aligned in relation to the laser beam. The scope is aligned to be parallel to the beam's direction when it is at the center of the primary window, and its field of view is bisected by the plane of the laser beam.

Figure 3.4.b is a rear quarter view showing the laser beam as it sweeps across a "pinhole" window that allows the beam to shine into the circuit chamber and be sensed by a photo diode in the circuit. Figures 3.4.c and 3.4.d show side views of the circuit chamber closed and opened, respectively. In figure 3.4.d, the pinhole window and the sensing photo diode are visible. The circuitry contained in the shroud is powered by +24 and -12 volts DC supplied from the battery pack. Output of the circuits are regulated +9 volts DC that powers the L-740 laser and the LEDs that illuminate the bubble levels, and a modulated DC voltage that powers the spin motor and maintains a constant spin rate of 18 Hz. The spin-frequency feedback required for this servo-control function is provided by the photo diode sensing the passing of the laser beam.

Figure 3.4.e presents a bottom view of the shroud. The receptacle space into which the top of L-740 fits is apparent. The figure also shows four thumb-screws used to secure the shroud to, and precisely align it with, the L-740.

3.1.3. The Tripod Base

The tripod base of the laser assembly is a heavy steel weldment with a slightly dished mounting surface that receives the L-740. The laser mounting dish is designed to allow for easily aligning the L-740 properly on the tripod (see section 3.3). The mounting dish may be rotated in the horizontal plane by loosening the hand knob beneath the upper structure (figure 3.1.c) and subsequently locked in place by tightening this knob. The adjustable legs of the tripod allow for nominal leveling of the mounting surface when the tripod is used on a cross-sloped surface. Each leg is made from 5/8-in. UNC threaded rod and terminates in a round foot pad, 1-1/2 in. in diameter, mounted to the leg with a ball-and-socket joint.

3.2. Assembly and Alignment of the Spinning Laser

The following describes the process of assembling, setting up, and using the spinning laser. It describes all the steps that would apply, assuming that the several components of the system have not yet been assembled, i.e., as in preparing to profile the first segment of a work day.

3.2.1. Locating the Tripod

Place the tripod aligning plate over the guidance tape at the appropriate position (see section 4.6.2). The notches in the plate should align with the tape and the arrow should point down range (figure 3.5).

Set the tripod in position with two foot pads located in the holes in the alignment plate and the third leg on the opposite side of the alignment tape (figure 3.1). Insure that the pads are firmly and evenly on the road surface.

Figure 3.5. Tripod alignment plate positioned over the guidance tape

3.2.2. Adjusting the Legs of the Tripod

The three legs of the tripod are adjustable. The goal in their adjustment is to establish the laser mounting surface (the surface of the "dish") in an approximately level condition and approximately 12-7/8 in. above the road surface, or, equivalently, with the top surface of the fixed structure 13 in. above the road surface (the mounting surface being 1/8 in. below this surface).

In general, it should only be necessary to perform these adjustments once for a given measurement section. Establishing the proper height within ±1/8 in. is more than adequate. The mounting surface need be leveled only to within the range of the leveling adjustments of the L-740. After adjusting, lock the legs in position. Two wrenches (a 15/16–in. open end and 7/16–in. socket driver) and a magnetic-base bubble level are supplied to aid in this adjustment process.

3.2.3. Mounting the L-740 on the Tripod

The L-740 has a very convenient magnetic base that allows it to be easily and securely attached to the mounting surface of the tripod. The diameter of the dished mounting surface is chosen such that the rotating head of the laser will be properly positioned when the front face of the magnetic base is set firmly against the edge of the dish (figure 3.6.a).
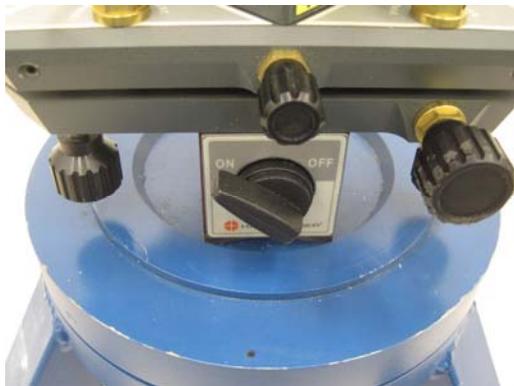
a. The L-740 properly mounted: the front corners of the magnetic base are firmly against the edge of the dished surface and the magnet switch is on.
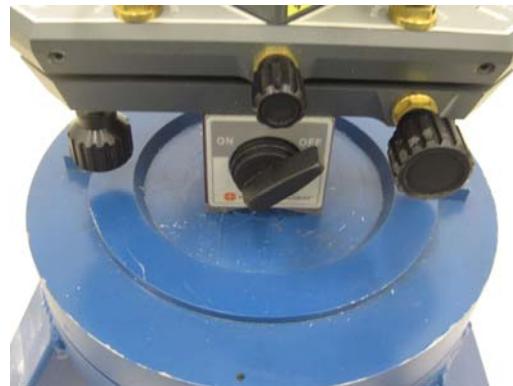
b. The L-740 improperly mounted: the magnetic base is not against the edge of the dished surface and the magnet switch is off.

Figure 3.6. Mounting the L-740 on the tripod

3.2.4. Mounting the Shroud Assembly on the L-740

Follow these steps to mount the shroud assembly onto the L-740:

- Back out the four nylon thumb screws sufficiently so that they do not protrude into the receptacle chamber (figure 3.4.e).
- Place the shroud on top of the L-740 so that, when facing the rear of the L-740 (i.e., the control-panel surface), the sighting scope is to the left and the circuitry chamber is to the right (figure 3.4.a).
- While firmly holding the shroud down onto the L-740 with one hand, progressively snug and tighten the four thumb screws with the other hand. This will firmly locate the forward and right sides of the L-740 against the same sides of the receptacle chamber.

- Plug the L-740 power cord into its mating connector on the right side of the shroud assembly (figures 3.4.a and 3.4.c).

3.2.5. *Powering the Spinning Laser*

To power the spinning laser, plug the cord from the battery pack into its mating connector on the right side of the shroud assembly (figure 3.4.e). First, turn on the laser beam and the bubble level illumination using the switches on the L-740 (figure 3.3). Then turn on the motor power using the switch on right side of the shroud assembly (figure 3.4.c).

Note that the servo system controlling the spin motor has a rather long time constant such that a change of motor speed may be audible over the first second or two of operation. Also, with all three elements turned on (laser, turret motor, and LEDs), the LEDs account for approximately 1/3 of the current draw from the power batteries. To make efficient use of battery power, the LEDs should be turned off except when needed for leveling the unit.

3.2.6. *Aligning the Spinning Laser*

Proper placement and height adjustment of the tripod, as described above, insures that the L-740 is properly located in three linear dimensions: longitudinal and lateral position relative to the section of road surface to be profiled and height above the surface. In addition, the L-740 must be aligned in three rotations: roll, pitch, and yaw. Proper roll alignment is accomplished by leveling the L-740 according to its roll bubble level. Alignment in pitch and yaw is accomplished using the alignment scope and the laser alignment target. Figure 3.7 illustrates the relationship of the various components of the system in establishing the centerline of the laser beam fan parallel to the guidance tape and some 22 in. directly above the centerline of the segment of road to be profiled. This insures that the laser is well aligned with the center of the laser target screens of the benchmark profiler as it travels the full length of the segment.

The alignment process is as follows:

- Position the benchmark profiler at the far end of the segment to be measured; use the setup control mode so that the profiler is accurately alighned with the guidance tape. Displpay the laser alignment target. (figures 3.7 and 3.8).
- Loosen the hand knob beneath the upper structure of the tripod and rotate the mounting dish so that the vertical crosshair of the sighting scope is approximately aligned with the black circle on the alignment target. Tighten the hand knob to secure the dish in place.
- Using the roll adjustments of the L-740 (figure 3.3), and observing its roll bubble level, level the L-740 in roll (figures 3.9). Note that the bubble level is very viscous and very sensitive, such that its response lags the adjustment appreciably; make adjustments slowly and be patient. Outside, particularly on sunny days, the bubble may be hard to see; a viewing shade is provided to aid in observing the bubble.
- Using the yaw and pitch adjustments of the L-740 and observing the alignment target through the sighting scope, center the crosshairs of the scope on the black circle of the target. Note that the scope has some parallax; locate your eye in order to center the visual field in the eyepiece.
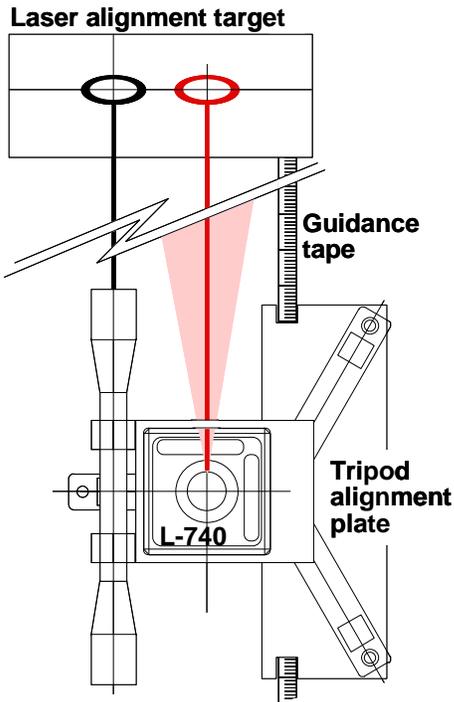
Figure 3.7. A schematic diagram of the lateral and yaw alignment of the spinning laser

Figure 3.8. The laser alignment target, in the display position, on the rear of the benchmark profiler

Figure 3.9. Top view of the spinning laser with bubble levels illuminated. The roll bubble is well centered; the pitch bubble is off center.

Figure 3.10. View through the sighting scope with the visual field centered and the crosshairs centered within the black circle

- Recheck, and if necessary, re-level the L-740 in roll.

- Check the alignment of the laser relative to the sighting scope. This step is not always necessary, but should be done at least during the first alignment of the spinning laser after mounting the shroud assembly on the L-740, or whenever there is any question of the relative alignment of the laser beam and the sighting scope. Turn off the spin motor. Carefully rotate the laser turret by hand, sweeping the beam very slowly across the primary window. On cloudy days, the beam should be readily visible as it sweeps across the reflective surface of the target. Even in sunny conditions, the beam should be visible

through the sighting scope. Confirm that the beam passes through the red and black circles of the target. Restart the spin motor.

- When alignment is complete, turn off the LEDs to preserve battery power.

3.3. The Laser Battery Pack — Charging and Replacing the Batteries

The battery pack for the spinning laser system is packaged in a yellow Pelican case containing three sealed, gelled-electrolyte, 12-volt lead acid batteries and an two automatic chargers (figure 3.11). The batteries are wired to supply +24 volts and -12 volts DC power to circuitry housed in the shroud. The two chargers are for the 12-volt and 24-volt systems, respectively. The batteries supplied are by MK Battery and are identified in table 3.1. Similar batteries are available under other brand names. The two larger batteries provides 24-volt power to the laser, the turret motor, the level illumination, and the control electronics. The smaller battery provides the negative 12-volt reference for the control electronics.

a. The battery pack with chargers and three batteries   b. The chargers removed for charging the batteries
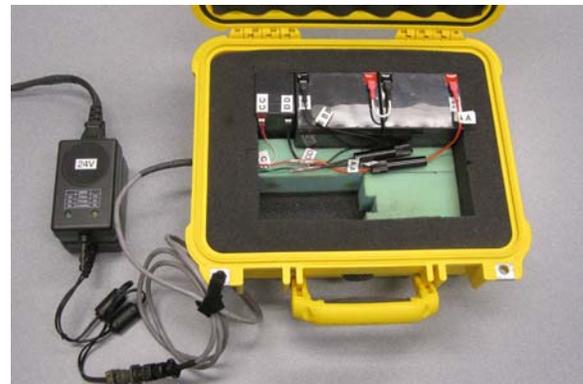
Figure 3.11. The battery pack for the spinning laser system

Table 3.1. Batteries in the spinning laser's battery pack

System function	MK Battery model	Rating	Dimensions (L x W x ,H)
Main power (two)	ES5-12	5 ampere hour	3.54" x 2.76" x 4.00"
Negative reference	ES1.2-12	1.2 ampere hour	3.82" x 1.69" x 2.09"

The current demand of the main-power batteries is composed of three elements: the laser; the turret motor, and the illuminating LEDs (plus a small, circuit overhead). With all three elements turned on, the LEDs account for approximately 1/3 of the current draw. To make efficient use of battery power, the LEDs should be turned off except when needed for illuminating the bubble levels.

When fully charged, the battery pack is capable of powering the spinning laser system in excess of 24 hours. Nevertheless, it is good practice to charge the batteries after each day of use. To charge the batteries, open the battery pack and remove the charger; plug the power cord of the charger into a standard 110-volt outlet and plug the cable from the battery pack into the connector at the rear of the charger. Leave the pack open while charging. From a low state of charge, a full charge may require 6 to 10 hours. After a typical days work, less time should be required. In any case, the chargers are

fully automatic and will shut off power to the batteries when they are fully charged. LEDs on the the chargers indicate their state of operation.

If the positive power supply drops below 21 volts, the turret motor for the laser may be unable to maintain the proper rotational speed. If the laser is unable to maintain approximately 18 Hz., the battery voltages should be checked. When and if the batteries need to be replaced, take care that the new batteries are connected properly. As delivered, the battery terminals and the wire leads are coded to indicate the proper connections. Carefully code any new batteries in the same way.

4. BENCHMARK-PROFILER MEASUREMENT PROCEDURES

This section describes the procedures for making profile measurements using the benchmark profiler.[2] The procedures described include the selection and preparation of the measurement segments, the actual process of profile measurement using the benchmark profiler, and the post-measurement surveying of the start and end points of the segments of the measured section. Detailed description of the operation of the benchmark profiler and of the ground-based spinning laser are described in sections 2 and 3, respectively.

4.1. Preparing for the Field Trip

Preparing for a field trip essentially means gathering and packing all the necessary equipment. Table 4.1 lists all the equipment needed for conducting measurements with the benchmark profiler.

UMTRI advises that the benchmark profiler be transported in the bed of a pickup truck that is equipped with an appropriate power lift gate. Alternatively, specially designed ramps could be used to load and unload the profiler from the bed of a pickup. Note, however, that <u>the profiler cannot be expected to negotiate slopes steeper than 1:16 solely under its own power</u>. Another possibility for transporting the profiler might be a specially designed trailer. In this case, note that the profiler is an instrument-quality device and that it does not have any shock-absorbing capability in its own suspension. <u>Hence, the ride quality of an ordinary utility trailer is likely to be unacceptable for transporting the profiler</u>. Any trailer used to transport the benchmark profiler should have a specially-designed suspension system.

4.2. Selecting the Measurement Sections

Select measurement section endpoints so that the qualitative properties (i.e., material type, macro texture type, etc.) and quantitative properties (approximate roughness level, joint spacing if applicable, etc.) of the pavement are uniform throughout. Avoid raised markings, distress, and rough transverse joints over the entire area that will pass within the track width of the benchmark profiler. If possible, extend these criteria 25 ft. upstream of the section starting point and 10 ft. downstream of the section ending point. The extra distance is needed for placement of the reference laser, set-up of the guidance tape, and lead-in and lead-out of the benchmark profiler.

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[2] With minor modifications, the procedures described are those used by the UMTRI team in September, 2010, while making benchmark profiler measurements of road sections at the Mn/Road Albertville facility and on an unused section of Route 10 near Junction City, WI. While it is certainly not necessary for other users to follow the described procedures to the letter —and there must surely be ways to improve upon these procedures in the future—these procedures constitute an efficient approach to using the benchmark profiler. Indeed, using the procedures described, two members of the UMTRI team profiled three pavement samples, comprising a total of 1712 ft., in a single day's work, nominally from 7:30 AM to 6 PM with a brief lunch break. Each pavement had previously been marked with the reference paint line, but all other steps in the measurement process were accomplished during this single day. Post-measurement surveying of the three sites was accomplished by two other individuals, and required considerably less than a full day's effort for them.

Table 4.1. Field-trip packing list

Benchmark profiler
- Benchmark profiler with cover, monitor/keyboard with vinyl sun shade, joystick
- Profiler 110vAC battery charger with timer
- Profiler jumper cables
- Lift-gate blocking fixture (if appropriate)
- Lift-gate extension ramp (if appropriate)

Spinning-laser
- Spinning-laser case:
  – Above the top layer:
    Tripod alignment plate; end-marker transfer plate
  – Top layer:
    Start/end marker strips (3); red and yellow lumber crayons; magnetic-base level; tripod adjustment wrenches; Allen wrench set; box cutter
  – Bottom layer:
    Hamar L-740; laser shroud assembly with spotting-scope lens covers; foam sun shade; marker-plate weights (6); tape measure(s); Ethernet cable; clip leads
- Spinning-laser tripod
- Spinning-laser battery pack

Guidance tape and anchors/weights
- Guidance tapes (2)
- Tape anchor (weighted tripod)
- Tape anchor (large blue weight)
- Foam-block weights (6)

Reference line
- ¼" polyethylene rope (600 ft., minimum)
- Light-duty wire-rope ratchet puller (come-along)
- Anchor plates (2)
- Striping machine
- White and back or blue marking chalk/paint

Surveying equipment
- Leica NA3 laser level with compatible tripod and invar rod

Computer equipment
- USB thumb drive, 2 GB minimum
- Laptop computer, suggested
- Software, suggested
  – Cognex In-Sight Explorer
  – DMC Smart Terminal
  – Microsoft Excel, Access
  – Microsoft SQL Server/Client
  – UMTRI data loader
  – Igor Pro (w SQLXOP.xop)/ Data reduction softwear
- Ethernet cable, suggested

Miscellaneous
- 12vDC-to-110vAC inverter(s) for powering laptop, etc, from automotive power outlet
- Hand cart(s) for moving equipment from segment to segment
- Run logging forms, clipboard, etc
- Large, light-duty tarp for on-site rain protection
- Standard tool set, mechanical
- Standard tool set, electrical/electronic

The lateral guidance of the profiler works best on test sections that are not rutted, and have uniform cross slope of less than 5 percent.

A test section should cover a distance at least four times the longest wavelength of interest, and a distance of ten times the longest wavelength of interest is preferable. For general applications, a robust benchmark-profiler experiment should include at least one test section that is at least 1,100 ft. long. On any test section, a section length of 475 ft. or more is recommended for profile comparisons related to the International Roughness Index.[3]

Select a lateral offset from the lane edge that will permit the entire benchmark profiler to stay within the lane. In addition, the profiler's support wheels should not track over a longitudinal joint, in another lane, or on a pavement shoulder. Select a location that will ensure that the guidance tape will not track along a longitudinal joint or any other "ridge" with steep transverse changes in elevation. For example, avoid placing the guidance tape over the ridge that appears between grinding head placements on a diamond ground pavement.

Inspect the entire footprint that will be covered by the benchmark profiler for the items mentioned above as well as short-duration features that may interfere with propulsion of the host cart, such as cores that were not filled properly, holes left by dislodged aggregate, or spalled or damaged concrete joints. The footprint of the profiler extends 11 in. to the right of the guidance tape and 17 in. to the left of the guidance tape. This includes a 6-in. wide area that will be covered by the RoLine, which extends from 1/4 in. to the right of the guidance tape to 5 in. to the left of the guidance tape.

4.3. Marking the Measurement Section

Measurement sections need to be precisely identified with semi-permanent markings on the road surface in order to insure that the benchmark profiler and the reference profilers under trial measure the same surface. The necessary markings include a longitudinal reference line and lateral start and end lines. Less permanent marks indicating the proper position of the benchmark profiler's guidance tape must also be provided (see section 4.5). Figure 4.1 presents a schematic diagram of the required surface markings in relation to the measurement section.
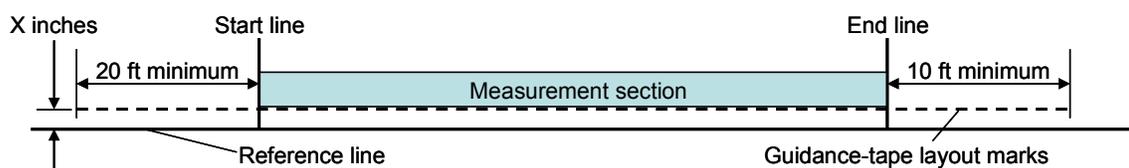
Figure 4.1. A schematic diagram of site preparation for the benchmark profiler (not to scale)

The reference line should be as straight as possible. A very effective technique is over-painting a rope that has been stretched very tightly.

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[3] For more detail, see: Karamihas, S. M., "Critical Profiler Accuracy Requirements." University of Michigan Transportation Research Institute Report UMTRI-2005-24 (2005) 115 p.

Using the vehicle anchor plates provided, and a light-duty hand ratchet winch (come-along), tightly stretch a polyethylene rope the prescribed distance to the right of the measurement section (figures 4.1 and 4.2). Insure that the rope is as straight as possible. Lifting and dropping the rope near its center, as is done with a chalk line, may help in this process. Using a striping machine, over paint the rope to provide a straight-line reference mark on the road surface. Note that the reference line should extend well beyond the start and end of the measurement section as is shown in figure 4.1.

a. The come-along attached to one vehicle anchor plate

b. The stretched rope weighted down at the come-along hook

c. The far end of the stretched rope anchor with the second anchor plate and vehicle

d. Painting the reference line

Figure 4.2. Stretching a rope with a come-along and anchor plates and painting the reference line

Using the stretched rope technique, or other technique as desired, mark the start and end lines of the measurement segment. Insure that these lines are square to the reference line.

4.4. Cleaning the Measurement Section

The entire measurement section must be free of debris such as loose aggregate, dirt, and leaves. Cleaning with and auto-broom is recommended. Whether an auto-broom has been used or not, operators should walk along the entire test section just prior to the measurements and remove any visible debris with a hand broom. Note that the 110-mm. swatch covered by the RoLine, which includes the guidance tape, is the most critical. However, the footprint of the host cart extends nearly 11 in. to the right of the track of interest and nearly 17 in. to the left. Debris under the host cart supporting wheels poses an unnecessary challenge to obtaining valid measurements.

4.5. Layout of the 300-ft. Guidance Tape and Identification of the Measurement Segments

4.5.1. General

A road-surface section to be profiled can be any length, although 1080 ft. is considered sufficient for the waveband of interest for most applications. For applications that relate to ride quality, there is no reason to measure a test section that is shorter than 30 ft. The benchmark-profiler guidance tape provided is 300 ft. long and a single layout of the tape can be used to profile up to 270 ft. of a measurement section (see figure 4.1). Moreover, benchmark-profiler measurements are generally made in 45-ft. segments. Hence, six segments totaling 270 ft. can be identified in a single layout of the tape. If the measurement section exceeds 270 ft. in length, the 300-ft. guidance tape will have to been laid out more than once.

The following procedure describes the initial layout of the guidance tape based on the start line of the entire measurement section. Subsequent layouts are similar but use the end line of the last segment of the previous layout as the start line of the new layout.

This procedure describes layout of the full 300-ft. length of the tape. In some cases, it may not be necessary to use the entire 300 ft. In that case, the "end" of the tape need only be at least 10 ft. beyond the end of the measurement section.

Benchmark-profiler measurements are typically made in 45-ft. segments. Exceptions to this are segments that are either slightly longer or slightly shorter and are meant to (1) avoid locating the start or end of a segment too near to the seams between concrete slabs, or (2) adjusting the last one or two segments of a tape layout in accordance with the end line of the measurement section. In any case, no single segment should be less than 30 ft. nor more than 50 ft. in length.

The benchmark profiler measures one segment at a time, typically making three passes (forward, reverse, forward) over each segment. The ground-base spinning laser is repositioned for the measurement of each segment.

4.5.2. Mark the Position of the Guidance Tape

The guidance tape should be laid out as straight as possible to the left of the painted reference line and on the right edge of the measurement area (figure 4.1). To do this, use a lumber crayon to mark the pavement the prescribed distance to the left of the reference line. Make an alignment mark approximately every 15 ft. along the length of the course. Marks should also be made very close to the start and end lines of the measurement section as well as 20 ft. ahead of the start line and some 10 ft. after the end line.

Figure 4.3. Two people marking the guidance tape position relative to the reference line

Two people working together can make these marks rather efficiently (figure 4.3). One individual positions a tape measure square to

the paint line and at a predetermined position over the paint line. The other makes the mark at a predetermined position on the tape. They then pace off about 15 ft. (five good strides) and the marking is repeated. Either or both individual may want to wear knee pads or carry a kneeling pad with them.

4.5.3. *Position the Guidance Tape*

Two people work together to position the tape.

Locate and anchor the start of the guidance tape as shown in figure 4.4. One person holds the tape at the start line such that the 20-ft. mark lines up exactly with the start line, and the tape overlays the lumber-crayon alignment marks at the start line. The other person stretches the tape taught at the zero-end (resisted by the person at the start line), also locating it over the alignment marks. The start of the tape is then anchored in this position using the weighted tripod.

| a. **Aligning the 20-ft. mark of the guidance tape with the start line** | b. **The start of the guidance tape anchored with the weighted tripod.** |

Figure 4.4. Locating and anchoring the start of the guidance tape

Stretch and straighten the guidance tape. One person walks the tape out to its full length along the measurement course, laying it close to the alignment marks in the process and taking the heavy steel anchor block along. Once the tape is fully extended, stretch the tape as tightly as possible (resisted by the other person; see the following paragraph) with the end more-or-less at waist height. With the tape fully tensioned, lower the tape to the ground carefully aligning it over the nearest alignment marks. (If there is not a mark very near the end of the tape, it is helpful to add such a mark.) Allow the tape to relax to a moderate tension and anchor it in position using the heavy steel anchor block.

The other member of the pair stays at the zero end of the tape. When his partner is ready to stretch the tape, he should bear down on the tripod with one foot in order to very securely resist the tension in the tape. Once the tape is relaxed, this person has completed tasks associated with laying out the tape and can proceed with moving equipment and setting up the spinning laser.

The person who laid out and stretched the tape should walk back to the start of the tape, carefully observing the lateral position of the tape relative to the alignment marks. If the tape was stretched tightly enough (and there was not too much lateral wind), in most case the tape will be directly over (fully hiding) the alignment mark. Where the alignment mark is visible, lift the tape just 2 or 3 in. and

place it over the mark. Lifting the tape higher than just a few inches tends to pull slack in the tape. If any slack in the tape is observed, re tension and re anchor the tape as described above.

4.5.4. *Mark the Start and End of the Measurement Segments and Anchor the Tape*

Segment marks are helpful in setting up for the measurement of each segment, but their primary value comes later during the surveying stage of the profile measurement.

Using a lumber-crayon, the person who laid out the guidance tape should mark the start/end positions of all the segments to be measured along the length of the tape. Use the guidance tape to identify the start/end positions, and make the marks on the over-paint of the reference line. Carefully place one of the weighted foam blocks on the guidance tape about 7 ft. beyond each start/end position. Assuming the tape is located with the start line at the 20-ft. mark, and that standard 45-ft. segments are to be used, segment marks would be made at 65 ft., 110 ft., 155 ft., etc; foam blosks would be placed at 72 ft, 117 ft, 162 ft., etc.

4.6. Benchmark Profiling

4.6.1. *General*

Two individuals work together to efficiently accomplish the benchmark profiling. One person is primarily responsible for setup and operation of the ground-based spinning laser (the *laser operator*), and the other is primarily responsible for the operation of the benchmark profiler (the *cart operator*). Efficient setup and profiling of one segment requires about 10 minutes. The actual measurement process by the benchmark profiler requires 5 minutes, assuming three passes over a 45-ft. segment.

Detailed descriptions of the operation of the benchmark profiler and the operation of the spinning laser were presented in sections 2 and 3, respectively. The *cart operator* and the *laser operator* must be fully familiar with the content of those sections, respectively.

It is assumed that, at the outset of this procedure, the profiler has been unloaded from its transport vehicle, its batteries are well charged, and it has been positioned adjacent to the measurement section near the start line of the initial segment. Also, an equipment cart loaded with the spinning laser, its battery pack, and the various other pieces of equipment (the laser alignment plate, the segment start/end marker strips, their weights, and the marker-transfer plate) has also been located near the start line of the initial segment.

Finally, users should be aware that the system that senses the passing of the spinning laser beam and triggers the exposure of the target camera can be disrupted by headlights or any other bright light source directed at the rear of the benchmark profiler. A foldable traffic sign requesting other drivers to turn off their headlights (see figure 4.5) has been provided and should be placed in the roadway upstream of the measurement section. It is also advisable to place a vehicle in position near the start of the section to block headlights of approaching vehicles (see figure 4.6).

4.6.2. Set Up and Profile the Initial Segment

Tasks of the cart operator

1. Position the start-line and end-line marker strips. Position the start-line and end-line marker strips as shown schematically in figure 4.7. Take care to align the markers square to the guidance tape. It is helpful to use the marker transfer plate as a "square" in this process.

2. Place a weighted foam block carefully over the guidance tape just before the segment start marker (i.e., near the 19-ft. mark).

3. Position the benchmark profiler over the guidance tape. Under operator control and using the joystick, position the profiler between the spinning laser and the start-line marker sufficiently well located over the guidance tape to enable DAS-control of steering. In general, this initial alignment is sufficiently accurate as soon as the *TapeStatus* gauge on the monitor screen reports *OK*. It is desirable, however, for the *TapeY* gauge to report a value within the range of ± 15 mm.

4. Position the profiler near the segment end-line. Carefully pick up the foam block in front of the profiler and place it on the tape behind the profiler. Switch the *Control Select* and *Run Mode* toggle switches to select the *SETUP* mode under DAS control. Drive the profiler forward toward the end of the segment stopping so that the end-line marker is under the profiler, more-or-less at mid wheelbase.

Please turn HEADLIGHTS OFF

Figure 4.5 .Traffic sign to be placed upstream of the measurement section

Figure 4.6 Vehicles positioned to block headlights of approching vehicles

Figure 4.7. Placement of the start-line and end-line marker strips for the first segment (not to scale)

5. Display the laser alignment target. Display the laser alignment target on the rear of the profiler as shown in figure 4.8.a.

a. Target displayed   **b. Target stowed**

Figure 4.8. The laser alignment target on the rear of the benchmark profiler

6. Stow the laser alighnment target. Once the laser operator has indicated that the laser is sighted, swing the alignment target back into its stowed position as shown in figure 4.8.b.

7. Return the benchmark profiler to the start position. With the profiler still in setup mode, slowly backup the profiler to the start area. Stop and pickup the foam block in the start area before running over it. Continue to back the profiler some three to four feet behind the start line.

8. Position the benchmark profiler for the start of the measurement. Still in the setup mode, slowly drive the profiler forward until the front wheels are aligned with the start-line marker strip (figure 4.9). Check the *TapeY* reading to insure that the profiler is well aligned laterally. Replace the foam block over the alignment tape behind the profiler.

Figure 4.9. The profiler in position to start the measurement of a segment

9. Initiate the profile measurement. Switch the *Run Mode* toggle switch to *TEST* mode. Insure the proper test parameters are set in the *Edit Parameters* and *Edit Header* dialogs. Cross check test ID and parameter information with the laser operator who is logging test data. Initiate the measurement by switching the *TestControl* toggle switch from *End* to *Start*.

Note: A standard measurement is composed of three passes over the segment, one forward, one reverse and the third forward. All three passes include a 5-second initial and final stationary dwell. The entire process is control by the DAS. A three-pass measurement of a 45-ft. segment requires 5 minutes.

Tasks of the laser operator

1. <u>Position the spinning laser</u>. Locate the laser aligning plate over the guidance tape close to the start of the tape (figure 4.10). This will place the center of the aligning plate at approximately the 1-ft. mark or 19 ft. ahead of the start line of the initial segment. Position the laser tripod using the alignment plate.

2. <u>Power up the laser</u>. Power up the spinning laser including the laser beam, the spin motor and the bubble illumination.

3. <u>Align the laser</u>. Level the laser in roll using the bubble level. Align the laser in pitch and yaw using the sighting scope. (The cart operator will have displayed the laser alignment target appropriately.)

Figure 4.10. The spinning laser in position at the start of the guidance tape

4. <u>Recheck the laser roll angle</u>. Recheck that the laser is level in roll after alignment and, again, before initiating the profile measurement. Signal the cart operator when alignment is complete.

5. <u>Shut off the LEDs.</u> To conserve battery power, shut off the illuminating LEDs when allignment is complete.

6. <u>Log the appropriate data</u> associated with the measurement of the segment. Appendix C presents a typical log sheet. In general, monitor the performance of the profiler during its three passes over the segment.

4.6.3. Set Up and Profile Subsequent Segments

Tasks of the cart operator

1. <u>Position the end-line marker strip</u>. While the benchmark profiler is making its three measurement passes over the previous segment, take a third start/end marker strip and a pair of marker weights to the area at the end of the next segment. Position the end-line marker strip 0.50 ft. passed the end line (figures 4.7). Take care to align the marker square to the guidance tape. It is helpful to use the marker transfer plate as a "square" in this process. Return to the end of the segment being profiled.

2. <u>Completion of measurements</u>. When the benchmark profiler has completed its three passes over the final segment, it will stop in a position short of the foam block that was placed 7 ft. past the segment end line, and with the end-line marker of that segment under the profiler. After it stops it will continue to gather data for five seconds during the "end dwell" period. When data collection is completed (i.e., *CartState* briefly reads "AllDone" and quickly changes to "WaitForRunning"), switch the *TestControl* toggle switch from *Start* to *End* and signal the laser operator accordingly.

3. <u>Move the profiler ahead</u>. Lift the foam block which is ahead of the profiler from the guidance tape and replace it over the guidance tape behind the profiler, taking care not to disturb the position of the tape. Switch the *Run Mode* toggle switch from *Test* to *Setup* and move the profiler forward the

length of the next segment, stopping so that the end-line marker of the next segment is under the profiler, more-or-less at mid wheelbase.

Note: This positioning of the profiler allows the laser to be setup and aligned, while avoiding the need to drive the profiler across the tape.

4. <u>Display the laser alignment target.</u> Display the laser alignment target on the rear of the profiler as shown in figure 4.8.a.

5. <u>Shift. the previous end-line marker to become the start-line marker</u>. Walk back to start of the new segment. Using the marker-transfer plate (which was previously placed to side in this area), shift the end-line marker for the previous segment to its new position as the start-line marker of the new segment (figure 4.11). Place the marker-transfer plate to the side.
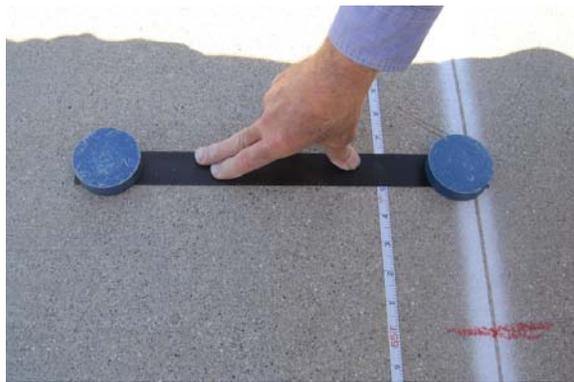
a. Secure the end-line marker plate in position.

b. Place the transfer plate edge firmly against the marker plate edge

c. Secure the transfer plate in position and transfer the marker plate to the opposite edge of the transfer plate.
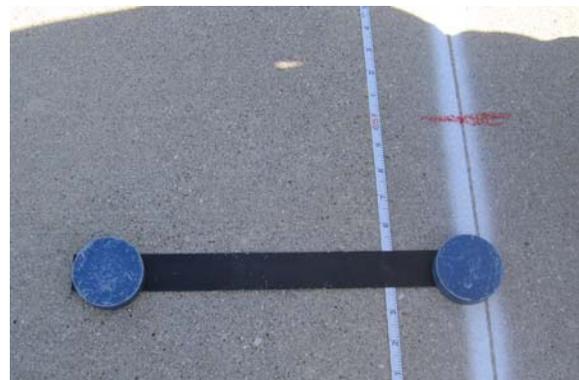
d. Weight the marker plate in its new position as the start-line marker.

Figure 4.11. Transferring a marker plate from the end-line position to the start-line position

6. <u>Retrieve the previous start-line marker and its weights</u>. Walk to the previous start line and retrieve the marker and weights.

7. <u>Return to the benchmark profiler</u>. Taking along the marker strip and its weights, and collecting the marker-transfer plate along the way, return to the profiler and set this equipment aside.

8. <u>Stow the laser alighnment target</u>. Once the laser operator has indicated that the laser is sighted, swing the alignment target back into its stowed position as shown in figure 4.8.b.

8. Return the benchmark profiler to the start position. With the profiler still in setup mode, slowly backup the profiler to the start area. Stop and pickup the foam block in the start area before running over it. Continue to back the profiler some three to four feet behind the start line.

9. Position the benchmark profiler for the start of the measurement. Still in the setup mode, slowly drive the profiler forward until the front wheels are adjacent to the start-line marker strip (figure 4.9). Check the *TapeY* reading to insure that the profiler is well aligned laterally. Replace the foam block over the alignment tape behind the profiler.

10. Initiate the profile measurement. Switch the *Run Mode* toggle switch to *TEST* mode. Insure the proper test parameters are set in the *Edit Parameters* and *Edit Header* dialogs. Cross check test ID and parameter information with the laser operator who is logging test data. Initiate the measurement by switching the *TestControl* toggle switch from *End* to *Start.*

Note: A standard measurement is composed of three passes over the segment, one forward, one reverse and the third forward. All three passes include a 5-second initial and final stationary dwell. The entire process is control by the DAS. A three-pass measurement of a 45-ft. segment requires 5 minutes.

Tasks of the laser operator

1. Power down the spinning laser. Power down the spinning laser (three switches) and disconnect the battery supply.

2. Transport the laser. Load the spinning laser, its battery supply and the laser aligning plate on the hand cart and move to the area 20 ft. short of the next start line.

3. Position the spinning laser. Locate the laser aligning plate over the guidance tape at a position such that its rear edge is close to 20 ft. ahead of the start line. This will place the center of the aligning plate at approximately 19 ft. ahead of the start line of the next segment. Position the laser tripod using the alignment plate.

4. Power up the laser. Power up the spinning laser including the laser beam, the spin motor and the bubble illumination.

5. Align the laser. Level the laser in roll using the bubble level. Align the laser in pitch and yaw using the sighting scope. (The cart operator will have displayed the laser alignment target appropriately.)

6. Recheck the laser roll. Recheck that the laser is level in roll after alignment and, again, before initiating the profile measurement. Signal the cart operator when alignment is complete.

7. Shut off the LEDs. To conserve battery power, shut off the illuminating LEDs when allignment is complete.

8. Log the appropriate data associated with the measurement of the segment.

4.6.4. Complete Profiling of the Final Segment and Move the Guidance Tape

<u>Tasks of the cart operator</u>

1. <u>Charge the profiler batteries</u>. When the profiler has completed the data gather process for the final segment, including the final *EndDwell* period, switch the profiler to operator-control and maneuver it off to the side in a position near an idling vehicle. Using the red palm button, shut down the 24-volt system. Use the special jumper cables to charge the profiler's batteries from the idling vehicle.

2. <u>Check data quality</u>. While it is not mandatory, it is recommended that the profiler data for the entire "tape" be offloaded, and, if the appropriate software is available, the initial quality checks should be conducted before moving the tape. (This may be done while the batteries are being charged.) This process will add a few minutes before the tape can be moved, but if additional passes are required for any segment, they can be done most efficiently with the tape still in position.

3. <u>Free the end of the guidance tape</u>. When appropriate, indicate to the laser operator that it is time to move the tape. Remove the heavy steel block from the end of the guidance tape and move the tape reel to provide slack in the tape for the following.

4. <u>Shift the previous end-line marker to become the start-line marker</u>. Secure the end-marker strip in position using your hand. Carefully slide the guidance tape from under the marker strip and move it aside. Transfer the marker plate from its position as the previous end marker to its position as the next start-line mark as shown in figure 4.11. <u>Take special care in the following steps not to move the marker plate</u>.

5. <u>Reel in the guidance tape</u>. Once the laser operator has removed the several weighted foam blocks from the guidance tape and the tripod anchor from the start of the tape, reel in the guidance tape until the 20-ft. mark is in the vicinity of the start-line.

6. <u>Position the guidance tape</u>. Once the laser operator has returned to the start area, layout the guidance tape in its new position as described in section 4.5.3, with the minor change that when first anchoring the start of the tape, align the 19.50-ft. mark of the tape with the leading (i.e., down-stream) edge of the start-line marker (figure 4.12).

   Note: Only in the case of the initial start-line marker strip, after moving the guidance tape, will the tape lie on top of the marker strip (figure 4.11). In all other cases, marker strips are placed over top of the guidance tape.
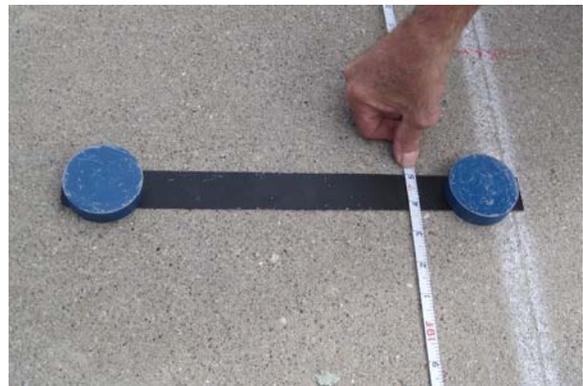
Figure 4.12. Aligning the 19.50-ft. mark of the guidance tape with the edge of the start-line marker.

<u>Tasks of the laser operator</u>

1. <u>Power down the spinning laser</u>. Power down the spinning laser (three switches) and disconnect the battery supply.

2. <u>Free the guidance tape</u>. When the cart operator indicates that it is time to move the tape, take the hand cart and walk back to the start of the guidance tape, picking up all the weighted foam blocks along the way. At the zero-end of the tape, pick up the tripod that anchors the tape.

3. <u>Transport equipment to the new starting position</u>. Return to the spinning laser and load it and its battery on the hand cart and continue on to the new starting area.

4. <u>Position the guidance tape</u>. Layout the guidance tape in its new position as described in section 2.3, with the minor change that when first anchoring the start of the tape, the 19.50-ft. mark should be aligned with the leading edge of the start-line marker (figure 4.11).

4.6.5. Complete Profiling of the Entire Section

Repeat section 4.6.2 through 4.6.4 as required to complete the profiling of the entire road section.

4.7. Backing up Profiler Data

Backup copies of the data files generated by the benchmark profiler should be made periodically during the testing day. Two convenient ways of doing this are:

- Copy data files from the DAS to a thumb drive installed in the available USB outlet on the control panel.
- Copy data files to a laptop computer connected to the DAS via the *DAS Cameras* Ethernet outlet on the control panel.

Copying to a USB thumb drive is certainly simpler and easier. Copying via an Ethernet connection may be faster.

Each test run generates fifteen data files, named as follows: Bytes, Data, Diagnostics, EndDwells, Floats, InMotion, Roline, RolineStamp, StartDwells, Summary, Summary2, Tape, TapeStamp, Target, TargetStamp, each file name being appended with the *RunID* number and the ".bin" designation. These files are written to the folder C:\Data\Cart. Figure 4.13 shows the listing of data files for runs number 680 and 681 in this folder.

The complete set of data files from a standard, three-pass test run, with pass length of 15 meters, consumes a bit less than 46 MB of disk space. The RoLine file constitutes more than 92% of this total; the combination of the Data, Diagnostics and Roline files make up more than 99%. A full and efficient day of testing can generate in the vicinity of 2 GB of data files. The hard disk of the DAS holds 74.5 GB of which something in excess of 70 GB is available for data.

To copy files, open the folder C:\Data\Cart on the DAS and order the listing of files by Date Modified. With this ordering, recent data files to be copied can easily be selected as a group. Copy the selected files in the usual manner to either the thumb drive or the laptop computer.

It is strongly recommended that data files not be deleted from the DAS in the field, and, in general, not be deleted from the DAS until at least two other copies exist on two independent media.
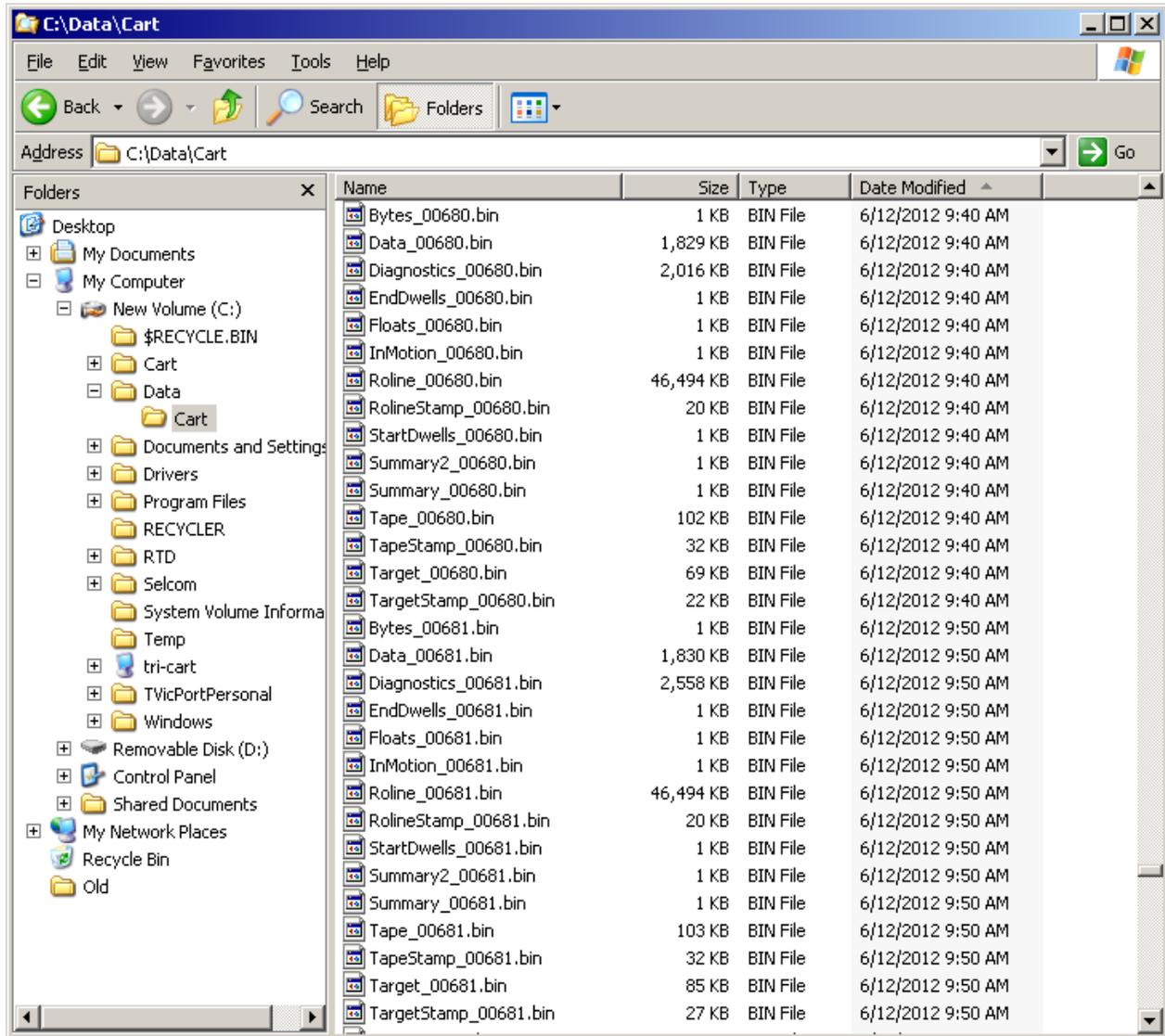
Figure 4.13. Data files on the DAS in C:\Data\Cart

4.8. Battery Management in the Field

The benchmark profiler is powered by four sealed, gelled-electrolyte, lead acid batteries of the type commonly used on electric wheelchairs. These four batteries power two separate electrical systems. Two of the batteries are connected in parallel and provide 12-volt power for the profiler's instrumentation system, of which the DAS, the RoLine 1130, the two machine-vision cameras, and the drive-wheel encoder are the primary elements. The other two batteries provide a 24-volt power source for the profiler's drive and steering systems, and the LED light bars that illuminate the field of view of the TapeCamera. Through the action of a relay system, these two batteries are connect in series whenever the master switch of the 24-volt system is switched on, but they are connected in parallel when the 24-volt system is switch off. This allows all four batteries to be charged simultaneously using either the 110-volt AC-to-12-volt DC charger or the special vehicle jumper cables provided.

When the profiler is in operation with the DAS program running, the actual supply voltages for both 12-volt and 24-volt systems are displayed in the lower right area of the monitor's screen, labeled as *InstrumentationBattery* and *MotorBattery*, respectively. When all batteries are fully charged, the *InstrumentationBattery* reading should be 12.6 to 12.8 volts and the *MotorBattery* reading should be 25.2 to 25.6 volts. (The MotorBattery reading will be 0 volts if the 24-volt master switch is off.) These readings may be somewhat higher shortly after the charger is disconnected. With the charger connected, the *InstrumentationBattery* reading should be 13.3 to 13.6 volts.

The InstrumentationBattery voltage should not be allowed to go below 11.5 volts. Below that level the DAS or other instrumentation may be in danger of shutting down unexpectedly due to insufficient power

The MotorBattery voltage should not be allowed to go below 23.0 volts. The performance of the drive motor, in particular, is very dependant of the supply voltage. Below 23 volts, performance will drop off substantially; below 22 volts, the servo amplifier will shut down.

To charge the motor batteries, the 24-volt master switch must be off (red palm button down).

The instrumentation batteries may be charged with the 12-volt system on or off.

It is recommended that all batteries be fully charged at the start of each work day. This can be assured by charging the batteries each evening using the 110 volt battery charger supplied. If the batteries have reached their minimum recommended voltages, a full charge will typically be reached in 6-10 hours. This will vary depending on the state of charge, whether the DAS is on, and whether both sets are being charged, or only the instrumentation batteries. It is not good practice to continue to provide an external current source to gelled-electrolyte, lead acid batteries, once they are fully charged. In general, remove the charging source once the batteries are fully charged. Do not leave the profiler's batteries on the charger for more than 12 hours.

It is also likely that the batteries will require charging periodically during a full working day. The batteries may be charged in the field whenever the profiler is stationary for a substantial period of time, for example, when the guidance tape is being laid out (see section 4.6.4) or during lunch breaks. To charge in the field, turn off the 24-volt system and charge using the special jumper cables attached to the battery of an idling vehicle. Charging may be done with the 12-volt system left on and with the DAS and instruments running, but charging the instrument batteries will be more efficient if the 12-volt system is shut down.

4.9. Surveying the Measurement Section

Measure the relative elevations of the endpoints of the measurement segments using a surveyor's rod and level. Use a rod and level with a specified precision of 0.1 mm. or less and a specified accuracy of 0.3 mm. or less.[4] Do not use a rod with a foot that is wider than 1 in. If needed, attach a secondary foot temporarily to the rod. Follow standard practices for conducting a rod and level

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[4] In the 2010 benchmark profiler experiment, the survey was conducted using a Leica DNA3 digital level and a bar-coded invar rod with a bubble level. A standard surveyor's tripod is also needed.

survey, with the exception of procedures explicitly described here. In addition, attempt to place the level so that it is reading the rod at a height that is 5 ft. or less above the pavement surface.

A given measurement section will include one more endpoint than the number of measurement segments. This is because, with the exception of measurement section limits, two segments share each endpoint. As described in Section 4.5.2, the segment endpoints will have been marked with a red lumber crayon during the layout of the guidance tape.

For this application, the quantity of interest is the elevation difference between consecutive measurement segment endpoints. With this in mind, develop a strategy for covering the measurement section by measuring groups of two or three segment endpoints at a time, in order that each elevation difference is measured at least twice. For example, as illustrated in figure 4.14, a measurement section that includes four segments has five endpoints, designated A through E. Measure points A and B in one tripod setup; A, B, and C in the next; B, C, and D in the third; C, D, and E in the fourth; and D and E in the fifth. Over measurement sections with many measurement segments, create a measurement strategy and a list of measurements before the survey begins to avoid missing a point. Label each point (with a letter, for example) to help organize data logging.
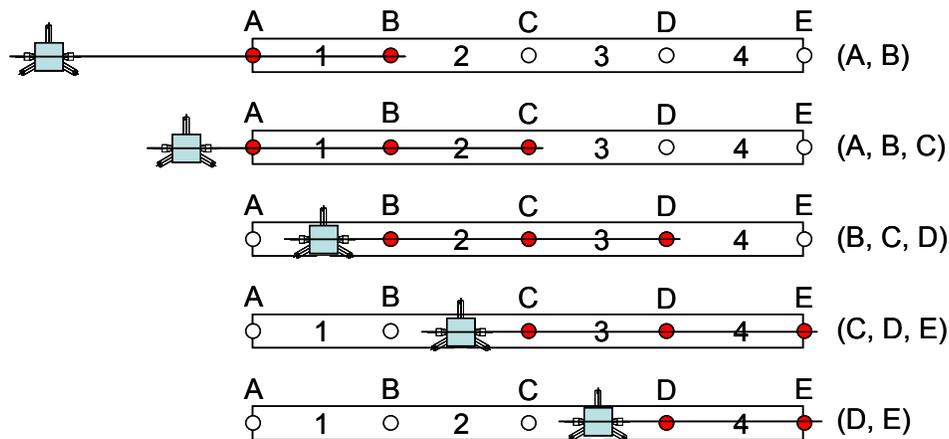
**Figure 4.14. A scheme for surveying a measurement section
with four segments (1 through 4) and five segment endpoints (A through E)**

Place the tripod at least 20 ft. away from the nearest point of interest. When the measurement sections are 45 ft. long or greater, surveying more than three endpoints in one tripod setup is not recommended. For each setup, place the tripod so that the level can be focused properly at both the nearest and farthest points of interest. As described in ASTM E1364, "it is recommended that the tripod for the level be located in line with the wheel track." This way, each group of readings can be done with minimal adjustment of the level's orientation.

Before leaving the site, verify that the elevation difference between each pair of adjacent measurement segment endpoints agree to within 0.5 mm. If not, repeat the measurement of elevation difference for those points until consistent values are produced by more than one tripod setup.

Accurate and consistent measurements depend heavily on accurate and consistent placement of the rod, and proper orientation of the rod. The rod operator must hold the rod steady, and use the bubble level to hold it vertically. Devise a way for the rod operator to signal the operator of the level

when the rod is oriented properly (and a way for the level operator to tell the rod operator when it is time to relax their stance). At each location, center the rod foot longitudinally adjacent to the red lumber crayon mark, and laterally at the center of the measurement track. If possible, perform the survey while the guide tape is still in place to help with lateral placement of the rod.

5. DATA HANDLING AND REDUCTION

This section outlines the elements of data handling and processing by which benchmark profiler data is reduced to useable form. Section 5.1 describes the primary data files from the profiler and the parameters in those files. Section 5.2 describes the process for obtaining special "level reference" pitch and roll angle data. Steps of the data reduction process are outlined in section 5.3.

5.1. Inventory of Outputs

5.1.1. Data Files

The benchmark profiler typically produces fifteen files per run. Ten of these files are used in the data reduction process. Most of the remainder serves diagnostic purposes. The fifteen files are:

Bytes — This file is not used in the reduction of profile data. It contains event data stored in byte format.

Data — This file provides encoder pulses (and distance) versus time at a regular interval of 100 times per second. The file also records frame "counts" from the RoLine, the TapeCamera, and the TargetCamera that are used, in conjunction with the TapeStamp and TargetStamp files, to time-sync data from these devices. This file is of primary importance in data reduction.

Diagnostics — As the name implies, this file provides data for diagnosing problems when systems in the profiler are not functioning properly. It records key diagnostics at a regular interval 100 times per second. This file is not used for data reduction.

EndDwells — This file provides statistics that describe the variation in reference laser height readings during intervals where the profiler is stationary at the end of each pass over a segment. One set of values is recorded per pass. This file is used during data reduction for data quality checks.

Floats — This file is not used in the reduction of profile data. It contains event data stored in single precision, real format.

InMotion— This file provides ranges of reference laser height, reference tape lateral position, and reference tape yaw angle for each pass over a test segment. One set of values is recorded per pass. This file is meant primarily for diagnostics; it is not used for data reduction.

Roline — This file provides elevation data within transverse lines 150 points wide at a constant rate of about 428.5 lines per second. This file is of primary importance in data reduction.

RolineStamp — Primarily for diagnostics, this file provides time on the 100 Hz. DAS clock for each set of "frames" saved from the RoLine. This file is not used for data reduction.

StartDwells — This file provides statistics that describe the variation in reference laser height readings during intervals where the profiler is stationary at the beginning of each pass over a segment. One set of values is recorded per pass. This file is used during data reduction for data quality checks.

Summary — This file provides parameters for identification of the run, operational control of the run, system health, and summary performance review. This file is of primary importance in data reduction.

Summary2 — This file provides additional parameters for identification of the run. This file is of importance in data reduction.

Tape — This file provides readings that define the position of the benchmark profiler relative to the steel guidance tape. These data are used for steering control, fine-tuning of longitudinal distance measurement, and lateral placement of the track of interest within each set of RoLine readings. Data are saved from each image analyzed by the TapeCamera. This file is of primary importance in data reduction.

TapeStamp — This file provides the time, on the 100 Hz. DAS clock, that each data sample is received from the TapeCamera. This file is used in conjunction with the Data file to time sync TapeCamera data. This file is of primary importance in data reduction.

Target — This file provides readings that define the position of the benchmark profiler laser screen relative to the reference plane defined by the spinning laser. These data are used as part of the composite elevation value at each location. Data are saved from each image analyzed by the TargetCamera. This file is of primary importance in data reduction.

TargetStamp — This file provides the time, on the 100 Hz. DAS clock, that each data sample is received from the TargetCamera. This file is used in conjunction with the Data file to time sync TargetCamera data. This file is of primary importance in data reduction.

The complete set of data files from a standard, three-pass test run, with pass length of 45 feet, consumes a bit less than 46 MB of disk space. The Roline file constitutes more than 92% of this total; the combination of the Data, Diagnostics and Roline files make up more than 99%.

Each file may be converted to an SQL data table using the UMTRI data loader. Table 5.1 presents the several numerical formats used in the raw data files and the corresponding formats in the SQL tables. Tables 5.2 through 5.11 list the variables (SQL channels) of the ten files (SQL tables) used in data reduction.

Table 5.1. Data formats

Data type	SQL data type	Description
byte	tinyint	one byte integer
single integer	smallint	two-byte integer
long integer	int	four-byte integer
very long integer	bigint	eight byte integer
single real	real	four byte real
double real	float	eight-byte real

Table 5.2. Channels of the Data file

Channel	Data Type	Channel	Data Type
RunId	integer	RolineCount	long integer
Time	long integer	TapeCount	long integer
Pass	byte	TargetCount	long integer
PassLength	single real	Distance	single real
Direction	byte	Encoder	long integer
RolineCenter	single real	LaserDistance	single real
NearZ	single real	CycleTime	single real
Speed	single real	CycleDuration	single real
CartState	byte		

Table 5.3. Channels of the Summary file

Channel	Data Type	Channel	Data Type
RunId	single integer	Temp 1	single real
StartTime	long integer	Temp 2	single real
EndTime	long integer	TapeAngleAverage	single real
TestSeries	long integer	TapeAngleMinimum	single real
Site	byte	TapeAngleMaximum	single real
Section	byte	TapeYAverage	single real
Segment	byte	TapeYMinimum	single real
SegmentLength	single real	TapeYMaximum	single real
PassLengthToDo	single real	NearZAverage	single real
PassesToDo	byte	NearZMinimum	single real
Pass	byte	NearZMaximum	single real
TestSpeed	single real	TimeofDay	double real
InstrumentationBattery	single real	MaxTapeScoreGap	single real
MotorBattery	single real	MaxTargetGap	single real
StartDwell	single real	DASVersion	byte
EndDwell	single real		

Table 5.4. Channels of the Summary2 file

Channel	Data Type
RunId	integer
TestSeries	long integer
Site	byte
Section	byte
Segment	byte
SegmentLength	single real
PassLengthToDo	single real

Table 5.5. Channels of the Roline file

Channel	Data Type
RunId	single integer
RolineSample	long integer
Point	byte
Value	single real

Table 5.6. Channels of the StartDwells file

Channel	Data Type
RunId	integer
Segment	byte
Pass	byte
Distance	single real
StartNearZAve	single real
StartNearZStdev	single real
StartFarZAve	single real
StartFarZStdev	single real

Table 5.7. Channels of the EndDwells file

Channel	Data Type
RunId	integer
Segment	byte
Pass	byte
Distance	single real
EndNearZAve	single real
EndNearZStdev	single real
EndFarZAve	single real
EndFarZStdev	single real

Table 5.8. Channels of the TapeStamp file

Channel	Data Type
RunId	single integer
Time	long integer
TapeSample	long integer

Table 5.9. Channels of the TargetStamp file

Channel	Data Type
RunId	single integer
Time	long integer
Target Sample	long integer

Table 5.10. Channels of the Tape file		Table 5.11. Channels of the Target file	
Channel	*Data Type*	*Channel*	*Data Type*
RunId	single integer	RunId	single integer
TapeSample	long integer	Target Sample	long integer
TapeX	single real	NearRoll	single real
TapeY	single real	Pitch	single real
TapeAngle	single real	NearZ	single real
TapeScore	single real	FarZ	single real
SteerCommand	single real	FarRoll	single real
TapeError	single integer	TargetError	short integer

5.1.2. Data Channel Descriptions

The following describes each channel that appears in one or more of the seven data files used in data reduction, and provides the units of the variable. The term "run" is used in many of the definitions. Note that a run refers to a single instance in which the operator sends the benchmark profiler on an automated data collection attempt. In a run, the profiler may make several passes over a segment of road, and the segment is typically only part of a test section of interest at a site. One of each of the files listed above is produced in each run, encompassing all of the passes within each.

CartState — The current state of operation of the profiler's control program. See table 2.4.

CycleDuration — Duration of the last DAS calculation cycle (msec).

CycleTime — Time since the last DAS calculation cycle started (msec).

DASVersion — DAS version number.

Direction — The direction of travel of the benchmark profiler for the current pass. A value of 0 indicates forward motion and a value of 1 indicates reverse motion.

Distance — Current longitudinal position of the profiler relative to its position at the start of the run (m). This is derived by applying a calibration factor to the output of the distance encoder at the drive wheel. The value of Distance increases during forward motion and decreases during reverse motion. (In 2012, the calibration value was set to 17,493 pulses/m.)

Encoder — Running count of pulses of the drive wheel encoder. The value of Encoder increases during forward motion and decreases during reverse motion.

EndDwell — Dwell time (i.e., time that the benchmark profiler collects data while still) at the end of a segment within a run (sec). This parameter is input by the operator (Edit Parameters dialog).

EndFarZAve — The average value of FarZ observed during dwell for cases when the end of a pass occurred with the profiler at the far end of the segment (mm.). ("Far" in this term refers to the laser target's proximity to the TargetCamera.)

EndFarZStdev — The standard deviation of FarZ observed during dwell for cases when the end of a pass occurred with the profiler at the far end of the segment (mm.). ("Far" in this term refers to the laser target's proximity to the TargetCamera.)

EndNearZAve — The average value of NearZ observed during dwell for cases when the end of a pass occurred with the profiler at the near end of the segment (mm.). ("Near" in this term refers to the laser target's proximity to the TargetCamera.)

EndNearZStdev — The standard deviation of NearZ observed during dwell for cases when the end of a pass occurred with the profiler at the near end of the segment (mm.). ("Near" in this term refers to the laser target's proximity to the TargetCamera.)

EndTime — Time of the end of the run since startup of the DAS program (csec.).

FarRoll — Roll angle of the far laser target relative to the line formed on it by the sweeping reference laser beam (deg). This is typically offset from absolute roll slightly, because of small changes in the profiler's orientation over time.

FarZ — Vertical position of the sweeping laser line on the far target at its intersection with vertical center line of the TargetCamera image (mm.). This is height of the laser sweep at the key point of interest in the center (laterally).

InstrumentationBattery — Supply voltage to the instrumentation system at the end of a run (volts).

LaserDistance — The current distance from the reference laser to the benchmark profiler's laser target screen (m.). This is derived by adding the current value of Distance to the initial LaserOffset. The LaserDistance is used by the TargetCamera program to select an optimal combination of exposure time and camera gain.

LaserOffset — The initial distance from the reference laser to the benchmark profiler's laser target screen at the start of a run (m.). The operator provides the (correct) offset distance prior to a run (Edit Parameters dialog).

MaxTapeScoreGap — The largest distance traveled during a run without a valid reading from the TapeCamera (m.). Distance is provided by the drive wheel encoder with an approximate calibration.

MaxTargetGap — The largest distance traveled during a run without a valid reading from the TargetCamera (m.). Distance is provided by the drive wheel encoder with an approximate calibration.

MotorBattery — Supply voltage to the motor systems at the end of a run (volts).

NearRoll — Roll angle of the near laser targets relative to the line formed on them by the sweeping reference laser beam (deg). This is typically offset from absolute roll slightly, because of small changes in the profiler's orientation over time.

NearZ — Vertical position of the sweeping laser line on the plane of the two near target screens at its intersection with vertical center line of the TargetCamera image (mm.). This is height of the laser sweep at the key point of interest between the two near targets. (This is also called Target Z (Near).)

NearZAverage — The average value of NearZ registered during a run (mm.). This is used for data quality checks.

NearZMaximum — The maximum value of NearZ registered during a run (mm.). This is used for data quality checks.

NearZMinimum — The minimum value of NearZ registered during a run (mm.). This is used for data quality checks.

Pass — The ID number of the pass over a test section. This number subdivides the data from a given run when the benchmark profiler makes multiple passes over a single segment in a given run.

PassLengthToDo — The distance the benchmark profiler is to travel in a single pass (m.). The PassLengthToDo is equal to the SegmentLength plus small additional distances at the start and at the end of the pass. (See figure 2.9.)

PassesToDo — The number of passes requested by the operator for the run (Edit Parameters dialog).

Pitch — Pitch angle of the profiler derived using the lines formed on target screens by the sweeping reference laser beam (deg). This is calculated using NearZ (Z_N) and FarZ (Z_F):

$$\text{Pitch} = [(Z_N - Z_F)/101.6 \text{ mm}] \cdot 180/\pi$$

Point — The point number of the RoLine measurement value of a given RoLine sample. A value is returned for each of 150 points (0 through 149) for each RoLine sample. (See section 5.1.3.)

RolineCenter — Height reading from the center column in the RoLine reading (mm.). This is provided for purposes of diagnostic and real-time data quality monitoring.

RolineCount — Frame index from RoLine synchronization pulses. (This is the same as "Frame Index" in the description of the Roline data file.

RolineSample — Sample number from the Roline. Unlike camera samples, RoLine samples do occur at a precise time interval. Linking RolineSample to "Time" is accomplished using a linear fit of RolineCount to Time in the Data file. (See section 5.1.3.)

RunId — The run ID number. The operator provides the RunID prior to each run (Edit Header dialog). To aid this process, the DAS automatically increments the RunId number during the set up for a run, so that, in practice, the operator need only monitor the RunId number.

Section — Section number. As of 2012, these were: (0) Dense Graded Asphalt, (1) Broom Finished Concrete, (2) Diamond Ground, (3) Longitudinally Tined, (4) Open Graded Friction Course, (5) Stone Matrix Asphalt, (6) Super Pave, (7) Transversely Tined, (8) Grooved Concrete, (9) Chip Seal, (10) Slurry Seal, (11) Pervious Concrete, (12) Burlap Dragged Concrete, (13) Level Reference. Section is manually selected by the operator from a drop-down menu (Edit Header dialog).

Segment — The segment number, indicating which segment is being measured within a test section. Segment number is manually entered by the operator, prior to the start of each run (Edit Header dialog).

SegmentLength — The length of the segment measured during a given run (ft.). This parameter is entered by the operator prior to initializing the run (Edit Header dialog). It is entered in feet as a convenience to the operator, given that the guidance tape is in feet.

Site— Site number. As of 2012: (0) Testing/Development, (1) GM Proving Ground, (2) MnRoad, (3) VA Smart Road, (4) NCAT, (5) TX DOT Certification Track, (6) WI DOT Certification Track, (7) PA DOT Certification Track, (8) MI DOT Certification Track, (9) OH DOT

Certification Track, (10) Ford Proving Ground, (11) UMTRI. Site is manually selected by the operator from a drop-down menu (Edit Header dialog).

Speed — Benchmark profiler travel speed (m./sec.). This is derived by differentiating the signal from the distance encoder at the drive wheel.

Start Dwell — Dwell time (i.e., time that the benchmark profiler collects data while still) at the start of a segment within a run (sec). This is parameter is input by the operator (Edit Parameters dialog).

StartFarZAve — The average value of FarZ observed during dwell for cases when the start of a pass occurred with the profiler at the far end of the segment (mm.). ("Far" in this term refers to the laser target's proximity to the TargetCamera.)

StartFarZStdev — The standard deviation of FarZ observed during dwell for cases when the start of a pass occurred with the profiler at the far end of the segment (mm.). ("Far" in this term refers to the laser target's proximity to the TargetCamera.)

StartNearZAve — The average value of NearZ observed during dwell for cases when the start of a pass occurred with the profiler at the near end of the segment (mm.). ("Near" in this term refers to the laser target's proximity to the TargetCamera.)

StartNearZStdev — The standard deviation of NearZ observed during dwell for cases when the start of a pass occurred with the profiler at the near end of the segment (mm.). ("Near" in this term refers to the laser target's proximity to the TargetCamera.)

StartTime — Time of the start of the run since startup of the DAS program (csec.).

SteerCommand — Steering-actuator command voltage (volts).

TapeAngle — Yaw angle of the steel tape relative to the profiler (deg). The value of TapeAngle increases as the profiler yaws clockwise relative to the tape.[5]

TapeAngleAverage — The average value of TapeAngle registered throughout a run (deg.). This is used for data quality checks.

TapeAngleMaximum — The maximum value of TapeAngle registered during a run (deg.). This is used for data quality checks.

TapeAngleMinimum — The minimum value of TapeAngle registered during a run (deg.). This is used for data quality checks.

TapeCount — Count of triggers sent to the TapeCamera. TapeSample and TapeCount should progress equally.

TapeError — True (i.e., value of 1) if an error occurs while processing the TapeCamera image.

TapeSample — Sample number from the TapeCamera. These samples do not occur at a precisely regular interval. Linking this with "Time" through TapeCount in the Data file is required to synchronize independent systems on the profiler.

TapeScore — The percent of pixel-match between the "trained pattern" of the steel tape searched for and the pattern found in the image captured by the TapeCamera (100 point scale). The

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[5] The output of the TapeCamera adheres to the ISO 8855 and SAE J670-2008 "Z-Up" vehicle-fixed coordinate system. In this system, leftward steer of the tape relative to the profiler is positive.

TapeScore will always be fairly high due to a match between the pattern of hash marks in the trained-pattern image and some pattern of hash marks on the captured image. The TapeScore will be highest when the numbers in the two images also match. In the latter case, the value of TapeX can be used for longitudinal distance. In any case, TapeY and TapeAngle can be used by the steering algorithm.

TapeScoreGap — The distance traveled since the last valid reading from the TapeCamera (m).

TapeX — Longitudinal position of the steel tape relative to the profiler (mm.). This provides the longitudinal position of the profiler along the steel tape within a given foot of distance. It is only correct when the correlation (TapeScore) is high.

TapeY — Lateral position of the steel tape (at a designated longitudinal location within the field of view) relative to the profiler (mm.). The value of TapeY increases as the profiler moves right relative to the tape.[6]

TapeYAverage — The average value of TapeY registered throughout a run (mm.). This is used for data quality checks.

TapeYMaximum — The maximum value of TapeY registered during a run (mm.). This is used for data quality checks.

TapeYMinimum — The minimum value of TapeY registered during a run (mm.). This is used for data quality checks.

TargetCount — Count of triggers sent to the TargetCamera. TargetSample and TargetCount should progress equally.

TargetError — True (i.e., value of 1) if an error occurs while processing the TargetCamera image.

TargetGap — The distance traveled since the last valid reading from the TargetCamera (m.). Distance is provided by the drive wheel encoder with an approximate calibration.

TargetSample — Sample number from the TargetCamera. These samples do not occur at a precisely regular interval. Linking this with "Time" through TargetCount in the Data file is required to synchronize independent systems on the profiler.

TestSeries — The ID number of the test series. This ID parameter is used primarily to distinguish between data that may be from the same site/section/segment but collected at different times. It is used primarily to link profiler data with the proper survey data.

TestSpeed — The commanded travel speed of the benchmark profiler throughout a given run (m/s). This is parameter is input by the operator (Edit Parameters dialog).

Time — Time since startup of the DAS program (csec.).

TimeofDay — Date/time at the end of a run since the turn from the 19th to 20th century (days).

Value — The measured relative distance from the RoLine to the road surface (mm.). One Value is returned for each of 150 points in the line associated with one RoLine sample. (See section 5.1.3.)

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[6] The output of the TapeCamera adheres to the ISO 8855 and SAE J670-2008 "Z-Up" vehicle-fixed coordinate system. In this system, leftward motion of the tape relative to the profiler is positive.

5.1.3. RoLine Data Packets

RoLine data are captured in packets as provided by the sensor. Each packet includes 60 profile arrays (i.e., lines), and each line contains a pre-determined number of "Z" coordinates. (The DAS directs the RoLine to store 150 points per line, and to only store vertical coordinates.) The profile arrays in each packet are preceded by other data that defined array size and other key information. Table 5.12 lists the pertinent information.

Table 5.12. Data in a RoLine packet

Channel	Data Type	Number of Values	Units
Not Used	very long integer	10	—
Count	very long integer	1	—
Width	very long integer	1	—
Channel	very long integer	1	—
Not Used	very long integer	1	—
Attributes	very long integer	3•Count	—
Roline Z	short integer	Count•Width•Channel	0.01 mm

The following provides excerpts from the RoLine manual (version 4.10.11) along with some notes defining the way the RoLine is used in the benchmark profiler.

Count — Number of profile arrays grouped in the message. The value is always 60.

Width — Number of range points per profile array. The DAS instructs the RoLine to provide 150 points that are centered within the sensor's range.

Channel — A value of 1 indicates that the RoLine is recording Z (vertical) data only, and a value of 2 indicates X-Z (sic) (lateral-vertical) pairs. The value is always 1.

Attributes — For each line, this provides the *time stamp*, the *frame index*, and a *tracking mode flag*.

Time Stamp — Capture time (microseconds) using the internal RoLine clock.

Frame Index — Frame index is read by monitoring synchronization pulses. The pulses progress at a rate of about 3000 per second. With tracking disabled an array (i.e., line) of profile data is captured for each 7 pulses. This is the mode commanded by the benchmark profiler. Thus, the data collection rate is about 428.5 Hz., and the pulses should progress by 7 each time a new sample is collected. Further, the time stamp on each packet of 60 lines of profile data should progress by 0.14 seconds. (In reality, the pulses progress at a rate close to 3003 per second, and the time stamp per packet progresses at a rate slightly slower than 0.14 seconds.)

Tracking Mode Flag — This indicates whether the Z data are obtained using a tracking window (0) or a search window (1). The benchmark profiler disables tracking mode, rendering this flag irrelevant. (A full search is performed over the entire detector range for every array.)

Roline Z — Profile arrays containing vertical readings in hundredths of a millimeter. One hundred fifty points are stored for each array from right to left before the beginning of data from the next array. Each packet will contain 60 groups of 150 points each. In raw form, the Roline Z values increase with distance from the sensor. Thus, a relatively low area within a line produces a higher value. A value of -32768 indicates that the sensor could not resolve the height for that "column" within the array.

5.2. Checking the Zero Calibration of Roll and Pitch Measurements

The zero calibration of the roll- and pitch-angle measures from the TargetCamera should be checked periodically and prior to each test program. To accomplish this, TargetCamera data are collected with the benchmark profiler located on a level surface and with the spinning laser carefully leveled in both pitch and roll.

It is preferable to make these measurements indoors where air currents are minimal and air temperature is stable. A nominally level surface of sufficient length to allow the laser assembly to be located approximately 33 ft. (10 m.) behind the profiler is required.

Clean the surfaces of the profiler wheels, and locate the profiler on a clean, flat surface that is level within ±0.03 degrees (2 minutes) as measured from wheel-contact point to wheel-contact point to wheel-contact point. If the actual surface available is not this level, a sufficiently level "surface" can readily be constructed by using sheet-metal shims of appropriate thickness at each of the three wheel positions, as can be seen in figure 5.1.a. Shims on the order of four inches square in the plan view are adequate in size, as the profiler will move fore and aft less than an inch during the data collection process.

| a. Profiler on leveling shims 30 ft. in front of the laser | b. View in the sighting scope with the laser leveled and aligned | c. Laser dot on the far left edge of the near laser target |
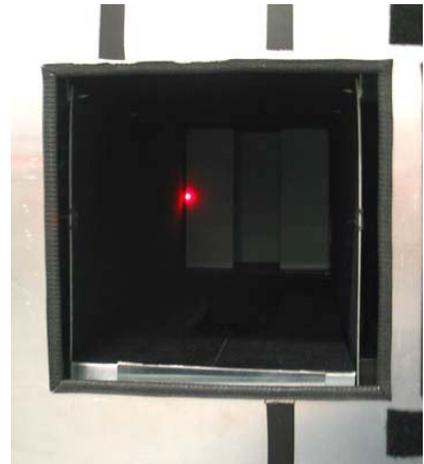
Figure 5.1. Set up of the benchmark profiler for collecting level reference data

Locate the spinning laser assembly approximately 33 ft. (10 m.) behind the profiler, directly in line with the centerline of the laser-target tunnel. The black tape line on the top surface of the profiler's cover can be helpful in aligning the laser. Note the position of the laser in the background of figure 5.1.a.

Level the laser in *both pitch and roll* using the laser's bubble levels and adjustment knobs. As shown in figure 5.1.b, align the laser in yaw using the sighting scope, locating the vertical crosshair about 2-½ in. left of the vertical centerline of the laser tunnel. Also, check that the horizontal crosshair of the sighting scope is close to the horizontal centerline of the tunnel. If necessary, use the adjustable feet of the laser tripod to establish the proper vertical position of the laser. Recheck that the laser is level in pitch and in roll and that the sighting scope is properly aimed.

Finally, insure that the laser is adequately aligned with the centerline of the laser tunnel. With the laser beam on, but the spin motor off, slowly rotate the laser turret by hand and observe that the beam illuminates the full width of the laser target, from the left edge to the right edge, without being shadowed by the sidewalls of the tunnel. See figure 5.1.c. Once this is done, start the spin motor.

Once the profiler and the laser are positioned and aligned, determine the LaserOffset (i.e., the actual distance from the laser to the near laser screen on the profiler) to within ±0.1 m. (±4 in.). Note that the longitudinal position of the near laser screen is indicated by the red tape on the side of the profiler's center floor panel.

There is no need to collect either RoLine data or TapeCamera data when collecting level reference data. Therefore, when booting the DAS and instruments, there is no need to power the RoLine. That is, step 2 of the booting procedure described in section 2.3.1 may be skipped. There is also no need to layout the guidance tape.

Conduct three "test runs" with the following non-standard parameters:

In the *Edit Parameters* dialog:
- *PassesToDo*: 1
- *LaserOffset*: 10 (m.) (or as measured)
- *StartDwell*: 120 (sec.)
- *IgnoreRolineErrors*: True
- *IgnoreTapeErrors*: True

In the *Edit Header* dialog:
- *Section*: 13 (Level Reference)
- *SegmentLength*: –4.05 ft. (This SegmentLength results in a value of PassLengthToDo of 0.006 m.; positive, but less than 0.1 in.)

In the *Edit Header* dialog, select the TestSeries and Site parameters associated with the data set to be processed, and use the standard *TestSpeed* of 0.15 m./sec.

Recheck the leveling of the laser prior to each of these three tests. Also note the *IgnoreRolineErrors* and *IgnoreTapeErrors* parameters must be reset to *True* prior to each test run.

Using these parameters, each of the three sets of data files collected will contain a 2-minute period of TargetCamera data collected during the start-dwell period when the profiler is stationary. This should result in a approximately 2160 TargetCamera data points collected during the start-dwell period of each run.

These data should be examined to determine the average measured values of roll and pitch during the start-dwell periods. If the measured values are found to be significantly different than zero, efforts should be made to determine why, and, if appropriate, the zero-offset parameters in the TargetCamera program should be adjusted accordingly. (See appendix I.)

5.3. The Data Reduction Process

A full, detailed description of the data-reduction calculations is beyond the scope of this document. Rather, this section will outline the steps of the process. This discussion will assume that the raw data files have been offloaded from the benchmark profiler and have been installed in an SQL database as tables (see tables 5.2 through 5.8). Note, however, the same calculation steps could well be conducted in other programming environments, e.g., Visual Basic, C++, etc.

In addition to the raw data tables, this discussion will refer to several "working" tables assumed to be available for aiding in the processing. Descriptions of these tables are given in appendix H.

5.3.1. Initial Data Checks

Prior to proceeding with the actual processing, the data can be examined for potential problems that may hinder or prevent determining the surface profile. Indeed, it is advisable to conduct these initial checks (as well as some of the data-reduction steps to be described in following sections) in the field upon the completion of measurements associated with each layout of the guidance tape. If the data taken are insufficient for any segment on the tape, it is far easier to repeat the measurements of that segment before the guidance tape is moved.

Table 5.13 presents a listing of potential data problems. Information similar to that of table 5.10 is contained in the working table, *ProblemCodes* (see appendix H). Problems 0 through 19 can be evaluated prior to any other processing of the data. (For problem codes 6, 7, 11, 13, and 17, the position of the start- and end-markers need not be known exactly; the approximate positions are adequate for these initial checks. Problems 20 through 30 are evaluate at various stages in the data reduction process. Results of the problem search are maintained in the table *ProblemsByPass* (see appendix H).

Subsequent data calculations are conducted for those passes *not* flagged with fatal flaws.

5.3.2. RoLine Samples: Times, Linear Fit and Problem Checks

For each RunID/pass, a linear fit is performed for time as a function of *RolineCount* using the appropriate range of values from the *Data* table. The resulting intercept and gain parameters are stored in the table *TimeOfRolineSamples* and can be used to assign a time to each *RolineSample* in the *Roline* table. A problem (problem code 21, table 5.10) is recorded in *ProblemsByPass* if the linear fit fails.

5.3.3. Location of the Segments Within a Section

By examining the *SegmentLength*s of the progression of segments in any section, the start and end positions of the segment relative to the start of the section are determined and are recorded in the *SectionFt* table, along with the ID information *TestSeries*, *Site*, and *Section*.

Table 5.13. Data problems, codes and threshold values

Problem Code	Problem	Fatal Code*	Alert Level	Fatal Level
0	Pass discarded by operator	1		
1	Pass missing	1		
2	Pass too short, m	1		
3	Roline: Avg freq out of range, Hz	1	(±) 0.5	(±) 0.5
4	CartState: Count too few or too many	1		
5	CartState: Faulty progression	1		
6	TargetCamera: TargetErrors between markers	1		
7	TapeCamera: TapeErrors between markers	1		
8	NearZ: Large Stnd Dev in Dwell, mm	2	0.3	0.5
9	Speed: Command speed not standard 0.15 m/s	1	≠ 0.15	
10	Speed: AvgSpeed out of range (0.15 reference), m/s	2	(±) 0.005	(±) 0.015
11	TapeCamera: Gap too large between markers, cSec	2	100	
12	TapeCamera: Avg freq low, Hz	3	10	8
13	TargetCamera: Gap too large between markers, cSec	2	14	20
14	TargetCamera: Avg freq low, Hz	3	17.3	16
15	NearZ: Out of range; ABS(nearZ) too large, mm	2	75	85
16	TapeScore: Percentage of "good" scores too low	3	20	
17	TapeY: Out of range between markers, mm	2	8	11
18	Section: Multiple segment lengths for this segment	1		
19	Section: No valid passes for segment prior to this segment	1		
20	Roline: LinearFit for Time = f(Sample) failed	1		
21	Markers: Problem with edge search for marker type	1		
22	Markers/Encoder: Gain out of range, tics/ft	2	20	30
23	TapeY: StDev of TapeY high, mm	2	1.5	
24	TapeY: StDev of DiffTapeY high, mm	2	0.35	
25	LandMarks: Count low, % of possible	2	90	
26	LandMarks:Large landmark gap, ft	2	2.5	
27	LandMarks: Linearity poor; StDv of residuals too large, tics	2	30	100
28	RolineProfile: Camera gap too large for NearZ fill in, csec	2	40	40
29	SurveyParameters: null result	1		
30	SurveyParameters: inconsistent height among passes, mm	2	4	

* Fatal codes: 1: always fatal. 2: fatal > fatal level. 3: fatal < fatal level.
Types 2 and 3 are not fatal if no value is given for the fatal level.

5.3.4. Segment Start and End Markers: Position in the Data Record, Linear Fit and Problem Checks

Since the relationships between the starting and ending position of the benchmark profiler and the start and end of the segment are closely established by the standard operating procedure and the calculation of *PassLengthToDo* (see figure 2.9 and the instructions associated with figure 4.7), the approximate position of the edges of the start- and end-markers in the data recorded (initially identified by the time parameter in the *Data* table) are known, a priori. The data of the *Roline* table corresponding to the near vicinity of these approximate locations can be examined to determine the precise position of the significant edges of the marker plates.

Figure 5.2 shows a graph of processed RoLine data in the vicinity of an end-marker plate. The vertical dimension presents the average of the center ten RoLine points from a given sample. The horizontal dimension presents the sample number, that is, the progression along the road surface. The marker plate is readily identifiable in the figure as a smooth "surface" elevated above the road; its edge, and hence the start or end of the segment data, can be precisely located by the steep transition down to the road surface. The selected sample on the leading edge of the end-marker identifies the

end of the segment. The *RolineSample* number so identified is used to identify the corresponding time, encoder count, and longitudinal position in the section (*sectionFt*) from the *SectionFt* table. The results are recorded in the *Markers* table.

After both start and end markers for a RunId/pass are identified, the average encoder gain (tics/ft) for the pass is calculated. If this gain is outside the expected range, a problem (problem code 22, table 5.10) is recorded in *ProblemsByPass* and problem types 18, 19, and 20 are reevaluated for the section.
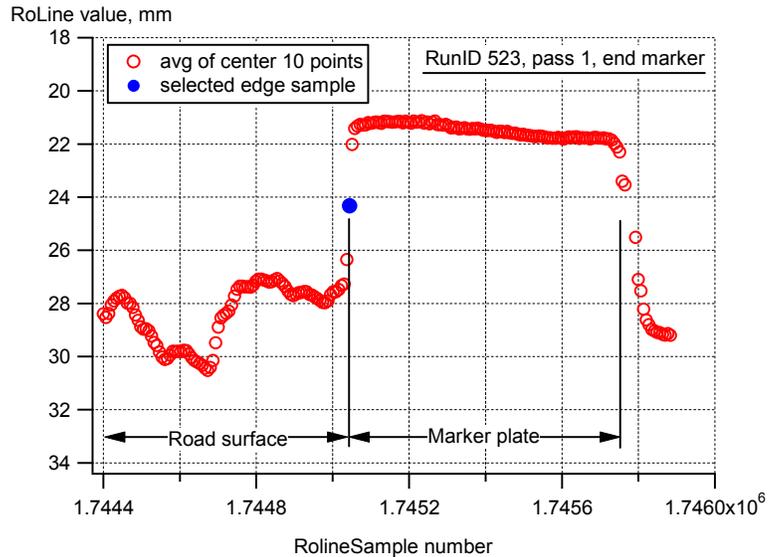
Figure 5. 2. An example of processed RoLine data in the vicinity of an end-marker plate

5.3.5. TapeCamera data: Times, TapeY Outliers and TapeY Scores

Data from the TapeCamera are initially process and augmented, and the results are recorder in the *TapePlus* table. The time of each *TapeSample* is determined by, first, indentifying the time of that sample in *TapeStamp* and, then, the immediate prior time at which *TapeCount* increments in the *Data* table.[7] The difference between the *TapeY* measurement and the average of the (one) preceding and (one) following measurements (*DiffTapeY*) is calculated. The sum of the (three) *TapeScores* for the current, preceding, and following samples (*SumScore*) is calculated. For the rare data samples where *DiffTapeY* is excessive (i.e., beyond what is physically reasonable, given the profiler's steering algorithm), a corrected value is calculated (T*apeYCor*). These results are recorded in the *TapePlus* table.

5.3.6. Guidance-Tape Landmarks: Identification, Position and Problem Checks

The data returned by the *TapeCamera* with each sample includes its estimate of the position of the centroid of the "trained pattern" (*TapeX* and *TapeY* in mm.) within the field of view of the TapeCamera. The centroid of the trained pattern is at a position 0.709 ft. (216 mm.) from the current foot hash mark (i.e., at a tape position of x + 0.709 ft. where x is the current foot).[8] Hence, with this value and *TapeX*, the position of the RoLine laser line on the guidance tape can be calculated. However, the TapeCamera *always* returns a value of *TapeX*, even when the true trained pattern is not in its field of view. The three, four, or five "correct" estimates that occur during each foot of travel

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[7] Times in a "Stamp" table are the times that data are received from the camera by the DAS. Times between exposure (data taking) and data return by the TapeCamera vary, requiring a "search" for the appropriate time of exposure.

[8] The value, 0.709, is dependent on the trained image of the TapeCamera and would have to be re determined were that image to be changed

can be identified by relatively high values of *TapeScore* in the same data sample. A so-called landmark is determined for each foot of travel by establishing the encoder and *sectionFt* values corresponding to the moment when *TapeX* is zero. It is, of course, highly unlikely that a TapeCamera sample is actually taken at this moment. Rather, this moment is determined by a linear fit and interpolation based on the several "correct" estimates for each foot.

The process begins by establishing an anchor landmark near the set of *TapeSamples* believed to have the highest quality data. The *TapePlus* table is searched for the *TapeSample* showing the highest value of *SumScore* between the markers of a given pass. This sample, plus several preceding and following samples are processed to determine *TapeX* and the encoder value corresponding to the moment of the *TapeSample*. The set of acceptable results from this process are used for a linear fit and the encoder value corresponding to *TapeX*=0 is determined from the parameters of the fit.

Having established the anchor landmark, the evaluation process of identifying landmarks is repeated at one foot increments (relative to the anchor) covering the range from the start to end marker. (One foot increments are based on the average encoder gain from start to end marker for the pass.) All the encoder values associated with *TapeX*=0 so determined, and the associated *sectionFt* positions are stored in the *LandMarks* table. This process does not always result in establishing a landmark for each and every foot of travel; occasionally the data set is of insufficient quality to calculate a reliable estimate.

Three problem checks (problem codes 23, 24, and 25, table 5.10) are made for each pass. One check determines the percent of possible landmarks found with less than 90% indicating a problem. The second check evaluates gaps without a landmark allowing no more than 2.5 ft. (i.e., no more than two successive missing marks). Finally, the linear fit is determined for encoder vs. *sectionFt* and the residuals (in encoder tics) are calculated and recorded in the *LandMarks* table. The standard deviation of the residuals is determined; any value in access of 30 tics (approximately 1.7 mm.) results in a problem recorded in *ProblemsByPass*. A value of 100 tics (5.7 mm.) is considered a fatal problem. Problem codes 18, 19 and 20 are then reevaluated for the section.

5.3.7. RoLine Data, Part 1: Time, Encoder Count, Section Position, Edge Point of the Measurement Field and TargetZ

The processing described in this section would likely be the last that might be done in the field prior to advancing the guidance tape to its next position. In as much as the RoLine data are taken at over 428 Hz. with 150 points in each sample, fully processing the RoLine data can be quite time consuming. The more intensive portions of RoLine data reduction are the lateral and longitudinal bridging computations. Accordingly, this section outlines preliminary processing of data from the RoLine, TapeCamera, and TargetCamera short of the bridging calculations.

The following calculations are accomplished for each measurement pass of interest.

Using the linear-fit parameters determined earlier (section 5.3.2), the precise time (i.e., more resolute than the 1-csec.) for each RoLine sample taken between the start and end markers is determined. The corresponding encoder count is then determined by interpolation based on the time and encoder data from the *Data* table. Similarly, the corresponding value of *TapeY* is determined by

interpolation based on the time and *TapeYCor* data from the TapePlus table. Using *TapeY*, the RoLine data point marking the right edge of the measurement field (see the "track of interest" in figure 1.6) is calculated using the following correlation:[9]

$$edgePoint = round((21.8 - 1.364\ TapeY)\ ,\ 0)$$

where the parameters in this equation are dependent on the trained image of the TapeCamera and would have to be re determined were that image to be changed.

Next, based on the previous results regarding the locations of the markers (section 5.3.4) and the landmarks (section 5.3.6), the position (*sectionFt*) of each RoLine sample is also determined by interpolation.

Finally, a value named *TargetZ* is calculated for each RoLine sample. *TargetZ* is the reference vertical measurement of the profiler directly above the RoLine, as determined from the sweep of the spinning laser on the target screens (figure 1.5). *TargetZ* is determined by first associating the value of (*Time*-3)[10] from the *TargetStamp* table with each TargetCamera sample in the *Target* table, and then interpolating to calculate *TargetZ* for each RoLine sample. Corrections are made to *TargetZ* to account for the measured roll and pitch of the profiler.[11]

The results of these calculations are recorded in the *RolineProfile* table.

5.3.8. RoLine Data, Part 2: Drop-Out Points in the Measurement Field, Lateral Bridging, Laser-to-Road and RoLine Profile

The second stage of the RoLine data calculations is the lateral bridging calculation.

A RoLine "value" is the measured distance from the RoLine reference height down to the road surface at the point of interest. Thus, larger values indicate depressions in the road surface; smaller values indicate peaks in the surface. Typical values are nominally in the range of 20 to 30 mm. The bridging calculation determines the representative single value for the surface, based on a very simple model of tire-tread penetration into the surface roughness.

The edge point found previously (section 5.3.7) defines the right edge of the 96-point measurement field. These points are initially examined for measurement "dropouts" that are revealed by large, negative values. The value for dropout points are set to 200 mm. If there are "too many" (more than 70) dropouts in any sample, the bridged value for the sample is set to 200 mm, indicating a "hole." If there are 70 or fewer dropouts, the bridging calculation proceeds.

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[9] An alternative method is to identify the RoLine data point at the left edge of the guidance tape and locate the measurement field relative to this point measurement (see figure 1.7). Comparison of the two methods using samples of the data from September of 2010, indicates that the two methods produce practically the same results, but that the *TapeY* approach is far less expensive computationally.

[10] Times in a "Stamp" table are the times that data are received from the camera by the DAS. Times of exposure (data taking) by the TargetCamera are consistently 3 csec. prior to receipt of the data by the DAS.

[11] Examination of data taken in 2009 and in 2010 indicate that these corrections are largely insignificant.

By a process of trial and error, the bridging calculation determines a reference value for the sample. An initial estimate of the reference value is chosen. For those points in the field that lie above the reference (i.e., are smaller values), the difference between the reference and the point value is calculated. For those points in the field that lie below the reference, a value of zero is assigned. The average of these 96 values is determined. The reference value is adjusted according to this result until the reference height yielding the target average of 0.7 mm ±0.0005 mm. is determined. The final reference value is recorded as the *BridgedValue* in the *RolineProfile* table.

Having determined the *BridgedValue*, the *LaserToRoad* distance is calculated from *TargetZ* and *Bridged value* and is also stored in the *RolineProfile* table.

5.3.9. Survey Data

The survey data must now be made available to proceed further with the data reduction process. Survey data must be entered into the *Survey* table. Note that for each *TestSeries*/*Site*/*Section* the initial values for *sectionFt* and for *Height* are identically zero. Subsequent points give the relative distance alone the section (*sectionFt* in ft.) and the relative road-surface height (*Height* in mm.) resulting from the survey.

5.3.10. Assemble Survey and Profiler Data: Road Elevation Relative to Start of Section

The survey data described the relative elevation of the road surface of the section at the start/end points of the several segments. The profiler measurements can now be adjusted such that they "match" these relative heights at the segment start/end intersections.

The foot of the survey rod is one inch wide (longitudinally). The average value of *LaserToRoad* of the *RolineProfile* table (section 5.3.8) is calculated over a span of ±0.5 in. relative to each segment start/end position. (Except at the start and end of the section, this requires using data from two successive runs.) The difference between this average and the associated survey height provides a correction value at the segment start/end points. Correction values for each *BridgedValue* of the *RolineProfile* table (section 5.3.8) are calculated by spatial interpolation. The road elevation values calculated by this process are stored in the *RolineProfile* table as *RolineRdElevation*.

5.3.11. Final Profile: Longitudinal Bridging

The final step in data reduction is longitudinal bridging. The *RolineRdElevation* data exist at the very high spatial density (approximately 0.35 mm. spacing) implied by the rapid scanning frequency of the RoLine and the slow travel speed of the profiler. Longitudinal bridging of these data reduces this density to one point every 5.08 mm. Bridging is accomplished by a process very similar to that described for lateral bridging in section 5.3.8. The bridging distance is 76.2 mm. (±38.1 mm. about the location of the final point). The reference bridging height is 0.7mm± 0.0005 mm; the same as for the lateral bridging calculation. The final result is recorded as *RdElevation* in the *Profiles* table.
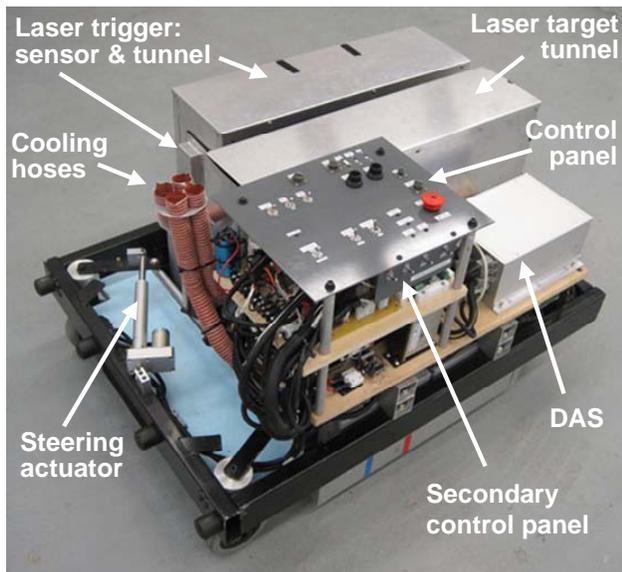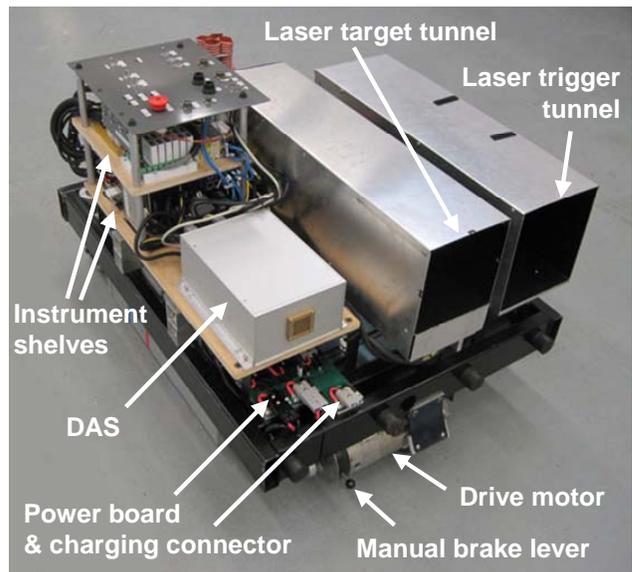
APPENDIX A.
BENCHMARK PROFILER PARTS LIST

A.1. Benchmark Profiler
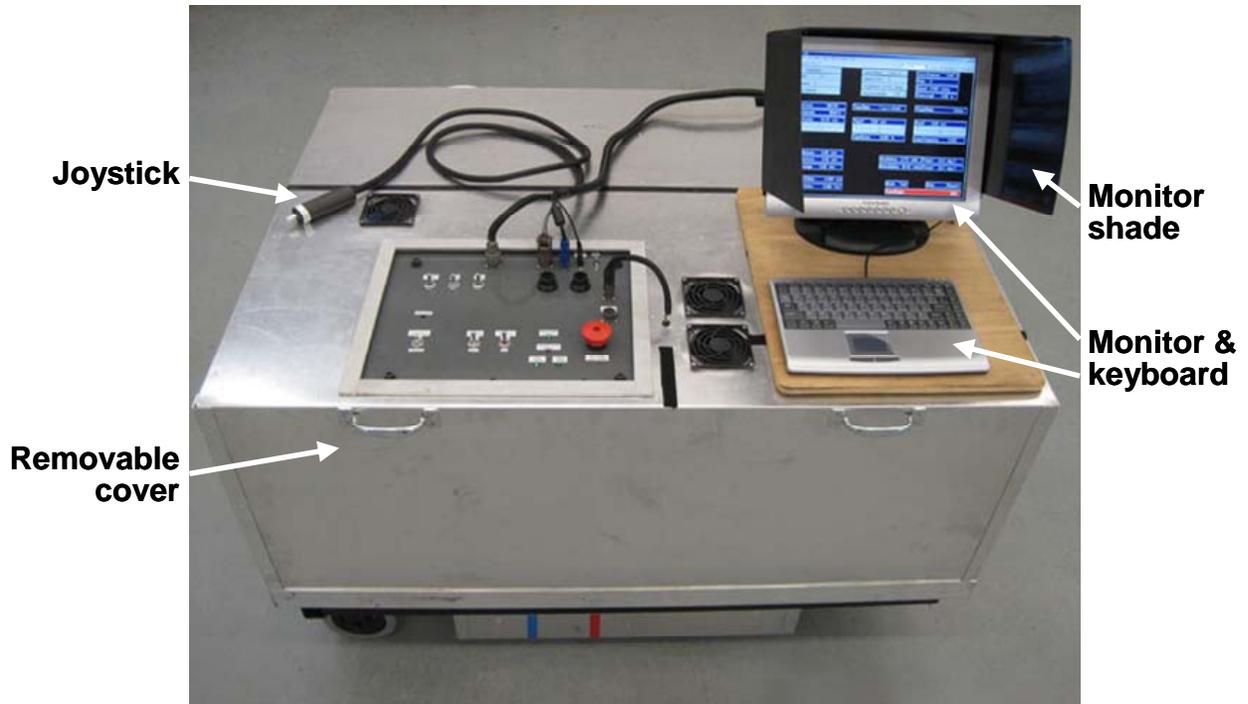
a. With cover, joystick, monitor & keyboard, and monitor sun shade

b. With the cover removed, from the left front

c. With the cover removed, from the left rear

Figure A.1. The benchmark profiler

A.2. Ground-Based Spinning Laser

Figure A.2. Hamar L-740

Figure A.3. Laser shroud

Figure A.4. Laser tripod base

Figure A.5. Sighting scope lens covers

Figure A.6. Laser tripod alignment plate

a. Closed

b. Top layer

c. Bottom layer

Figure A.7. Laser case

Figure A.8.
"HEADLIGHTS OFF"
foldable traffic sign

a. Battery pack closed

b. Open showing batteries and chargers

Figure A.9. Laser battery pack

A.3. Guidance Tape

Figure A.10. 300-foot guidance tape (3)

Anchor, tripod   Foam block weights   Anchor, block

Figure A.11. Guidance tape anchors and weights

A.4. Marker Strips
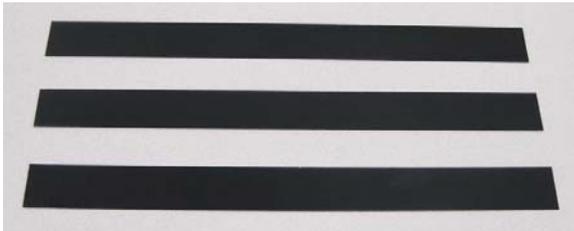
Figure A.12. Marker strips

Figure A.13. Marker-strip weights

A.5. Ancillary Equipment

Figure A.14. Marker-strip transfer plate

Figure A.15. Sun shade for laser bubble-levels

Figure A.16. Stretched-rope anchor plates

Figure A.17. Battery jack

Figure A.18. 110-volt battery charger for the profiler

Figure A.19. Jumper cables for the profiler

Figure A.20. Lifting hardware: spreader, cables and crossbar

Figure A.21. Lifting hardware in use

Figure A.22. Equipment cart

Lumber crayons	Wenches for laser tripod legs	Magnetic-base level

Figure A.23. Miscellaneous support equipment

APPENDIX B.
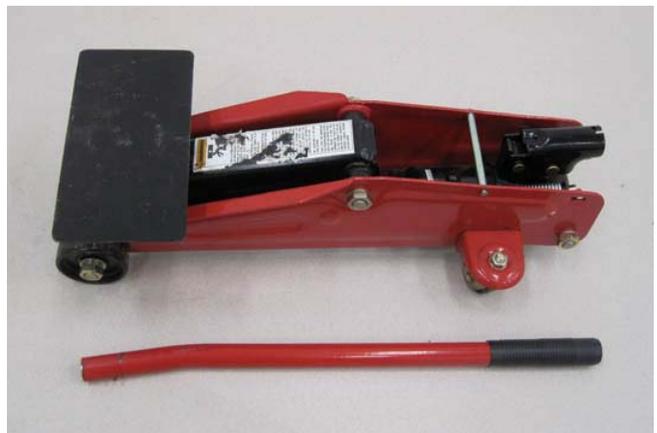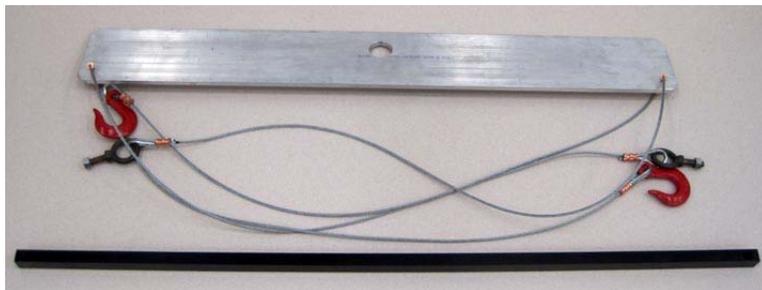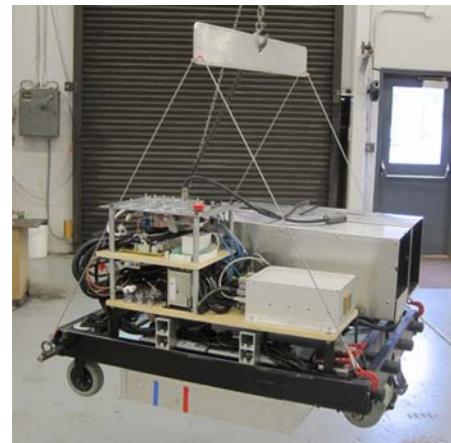## ASSIGNING NEW IP ADDRESSES

B.1. Introduction

There are six computers onboard the benchmark profiler: the UMTRI DAS plus embedded computers in the RoLine 1130, the two machine-vision cameras (TapeCamera and TargetCamera), and the two servo controllers (SPEED controller and STEER controller). All six computers are capable of communicating via Ethernet, and all six have assigned IP addresses. The DAS, the RoLine, and the two cameras communicate with one another via Ethernet during profiler operations; these four computers *must* have compatible IP addresses and the necessary host IP information. Five of the six computers (the RoLine excluded) are accessible by external Windows computers via Ethernet connectors on the control panel. Accessing the DAS externally may be necessary for off loading profile data. Accessing the cameras and the controllers externally is not required routinely, but may be necessary occasionally. Hence, practically speaking it is desirable for these five computers to be assigned IP addresses compatible with the user's own network and/or computer.

B.2. The Networks

Figure B.1 provides a simple schematic of the three Ethernet networks of the benchmark profiler.
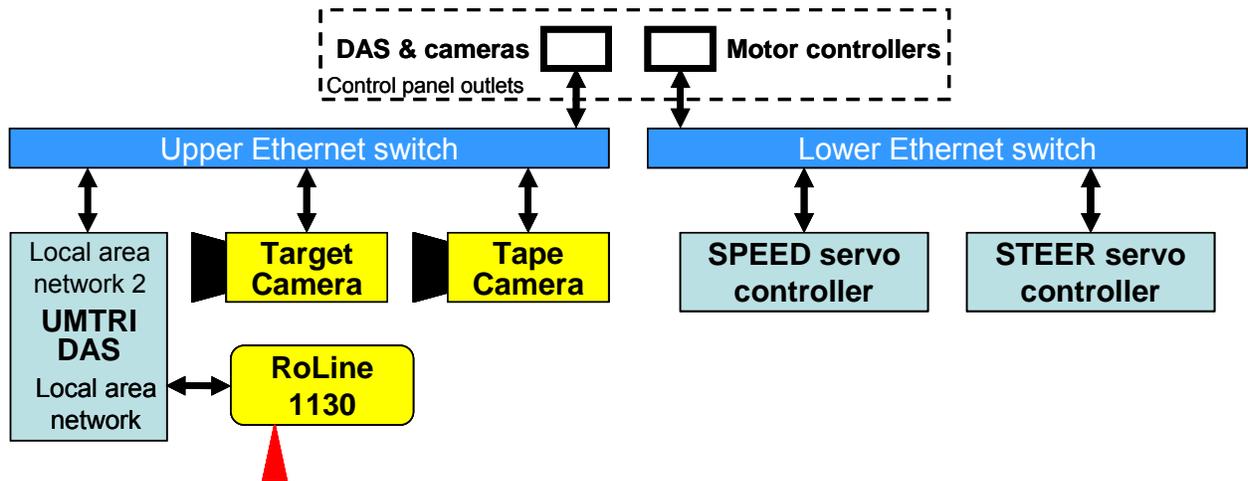
Figure B.1. Schematic diagram of the Ethernet connections of the benchmark profiler

As indicated in figure B.1, the benchmark profiler has three Ethernet networks. The DAS communicates with the two machine-vision cameras on one network that is accessible via an Ethernet outlet on the control panel. The DAS communicates with the RoLine via a second, private network. The third network provides external access to the two motor controllers via a second Ethernet outlet on the control panel. Communications on the two networks involving the DAS are integral to the operation of the benchmark profiler, and provide for external access to the DAS and the cameras. The motor-controller network is provided only for external access and plays no role in the regular operation of the profiler.

B.3. Compatibility of IP Addresses

The IP address of the RoLine 1130 is fixed by the manufacturer, can not be altered, and is generally not compatible with public networks. Hence, the DAS communicates separately with the RoLine through a private network.

Communication between the DAS and the two cameras on their network during profiler operation *requires* that the IP addresses of these three computers be on the same subnet. For purposes of external access, it is also desirable that this subnet address be the same as on the user's network and/or of the IP address of the Windows computer the user may use for offloading data. Alternatively, a computer using Dynamic Host Configuration Protocol (DHCP) can be used for external access.

With respect to the proper operation of the benchmark profiler, there are no requirements for the IP addresses of the motor controllers. (Indeed, since it is possible to access the controllers via their serial interface, strictly speaking, there is no *requirement* that the controllers be assigned IP addresses at all.) However, for convenience of external access, it is advisable that they also be assign IP addresses within the same subnet used for the DAS and cameras.

If the IP address of the DAS, cameras, and controllers are all on the same subnet, the two networks may be combined with a jumper between the control-panel outlets, allowing the DAS to communicate with all four devices for maintenance or diagnostic purposes.

B.4. Setting Network and Host-Table IP Addresses

As delivered, the IP addresses assigned to the DAS, the two cameras and the two controllers are compatible with one another, and the appropriate hosts for the DAS and the cameras are identified in their respective host tables. However, these addresses may not be compatible with the user's network or with the user's computer if that computer is not using DHCP.

In this as-delivered state, new IP addresses may be assigned, and the host tables edited, using the DAS computer. (Later, when IP addresses compatible with the user's network or computer have been set, they can also be change using an external Windows computer.) To do so, follow the steps below.

1. Establish, and have on hand, a written list of the five IP address to be assigned. Also have on hand the additional Internet Protocol (TCP/IP) information for the UMTRI DAS as is appropriate for the user's network (subnet mask, and default gateway, and the DNS addresses of the preferred and alternate servers).

2. Boot the system and interconnect the network switches. Switch on the master 12-volt power and the camera power. Be sure the brake is set on the drive motor, and switch on the 24-volt power. Connect an Ethernet cable between the two Ethernet outlets on the control panel to create a single network with all five computers to be addressed. Wait for the DAS computer to boot.

3. Set the IP addresses of the motor controllers first.

3.1 Run the *DMC Smart Terminal* program using the shortcut icon on the DAS desktop.

3.2 Connect to the STEER controller. The "Select Motion Controller" dialog box will open immediately upon starting the *DMC Smart Terminal* program (figure B.2). Select Controller1, the STEER controller and click OK.
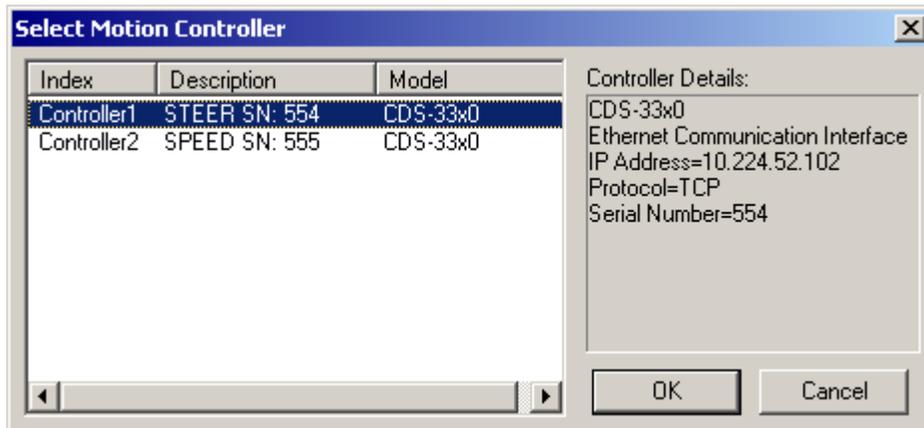

Figure B.2. The *Select Motion Controller* dialog box

The main window will now appear (figure B.3). This window is subdivided into three smaller windows. In the upper left window, typed commands can be sent directly to the controller; all commands are composed of two, upper-case alpha characters followed by the necessary parameters. Responses from the controller to those commands are displayed in the lower left window. Controller programs are created and/or edited in the large window to the right. Note that the program editing window has its own pop-up menus.
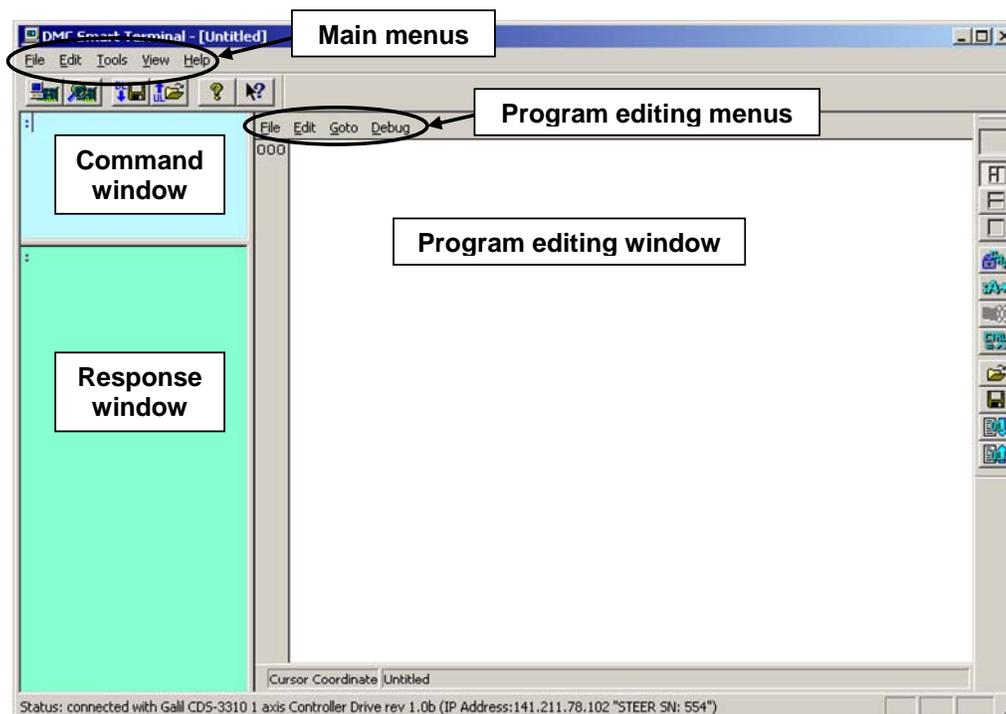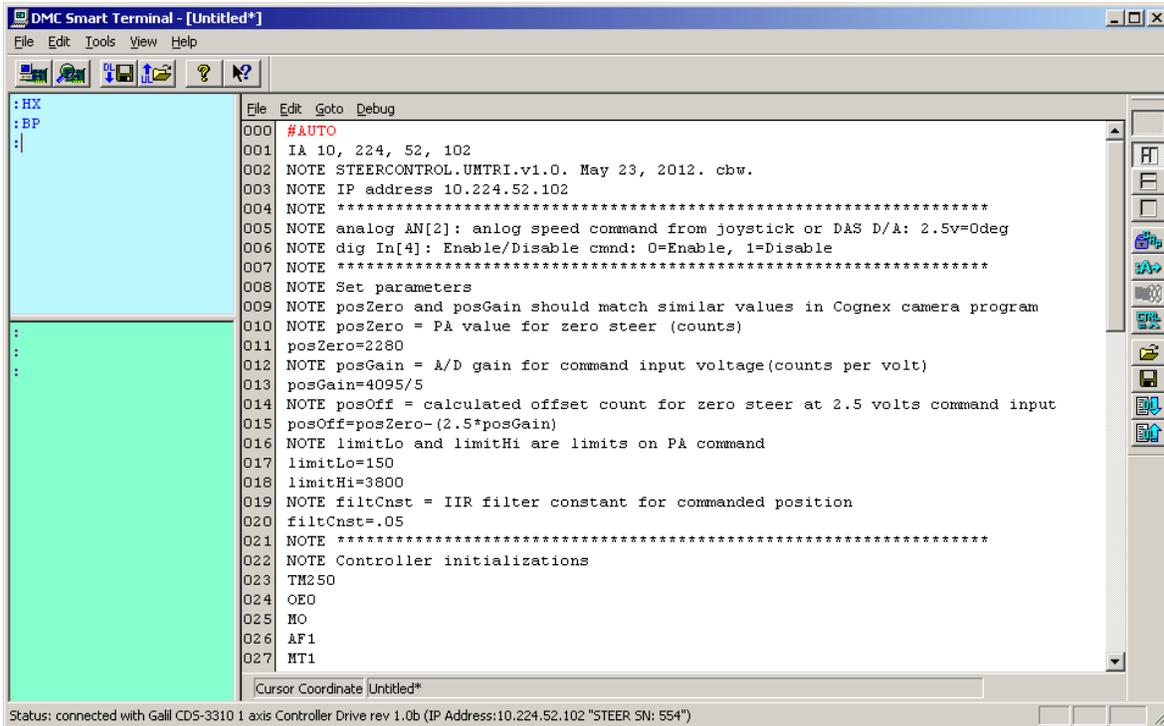

Figure B.3. Main window of the *DMC Smart Terminal* program

3.3 Halt program execution in the controller (figure B.4). Click on the command window, and type HX [Halt eXecution] and Enter. (Commands must all be in upper case.) The steer control program will stop executing.

Figure B.4. The *DMC Smart Terminal* window after resetting the controller IP address

3.4 Upload the program from the controller (figure B.4). Open the File menu <u>of the program editing window</u> and select "Upload from Controller." The current controller program will appear in the editing window, and a dialog indicating the successful upload should appear.

3.5 Edit lines 001, 002, and 003 (figure B.4). Line 001, the first executable line of the program, contains the IA [<u>IP A</u>ddress] [12] command. The IP address that is set is indicated by the four numbers, separated by commas, in the parameter list. Lines 002 and 003 contain non-executing NO [<u>NOTE</u>][11] commands. All characters following the NO are ignored by the program. These lines are used to document the version of the program and the IP address. Edit lines 001, 002, and 003 appropriately to establish the new IP address and to properly identify the new version of the program.

3.6 Save the new version of the program. Open the File menu <u>of the program editing window</u> and select Save As. Save the new version of the program, with an appropriate name, to a DAS file.

3.7 Download and "burn" the new program to the controller (figure B.4). Open the File menu <u>of the program editing window</u> and select "Download to Controller." A dialog window indicating the successful download should appear. Select the Command Window and type BP [<u>B</u>urn <u>P</u>rogram] and Enter. There will be a slight pause before program control is returned to the keyboard. The new version of the program is now installed in the controller's memory. However, the new program has not executed, and the controller retains its old IP address. The new IP address will be assigned the next time the controller is booted. The new IP address will be "registered" during step 3.12.

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[12] Commands of the controller language are case sensitive and <u>must be capitalized</u>.

3.8 Disconnect from the STEER controller. In the Tools menu, select "Disconnect from Controller."

3.9 Connect to the SPEED controller. In the Tools menu, select "Select Controller..." The "Select Motion Controller" dialog box will open (figure B.2). Select Controller2, the SPEED controller and click OK.

3.10 Reprogram the SPEED controller. Repeat steps 3.3 through 3.8 for the SPEED controller, and then exit the *DMC Smart Terminal* program.

3.11 Reboot both controller cards. Shut down the *DMC Smart Terminal* program. Switch off the 24-volt power, wait a few moments, then switch the 24-volt power back on.

Figure B.5. The *Edit Registry* dialog

3.12 Register the new IP address of the STEER controller. Restart the *DMC Smart Terminal* program. When the "Select motion controller" dialog box appears (figure B.2), click on "Cancel." From the "Tools" menu, select "Controller Registration.." The "Edit Registry" dialog box will appear (figure B5). Select Controller 1, the STEER controller, and click on "Edit Controller Properties. The "Controller Communications Parameters" dialog will appear (figure B.6). Select the "Ethernet Parameters" tab and click on "Set IP Address." After a moment, a message box will appear (figure B.7) that indicates that the IP address is already assigned to the controller, and asking if you want to continue using this address. Click "Yes" and controller registry will be reset to the new address.
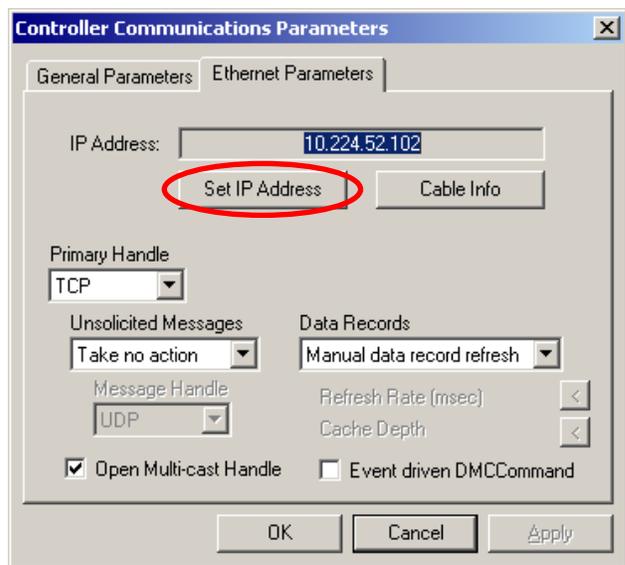

Figure B.6. The *Controller Communication Parameters* dialog

Warning: <u>DO NOT CLICK ON "NO"</u> in the "IP Address Already Assigned" message box. Doing so will cause a master rest of the controller card.

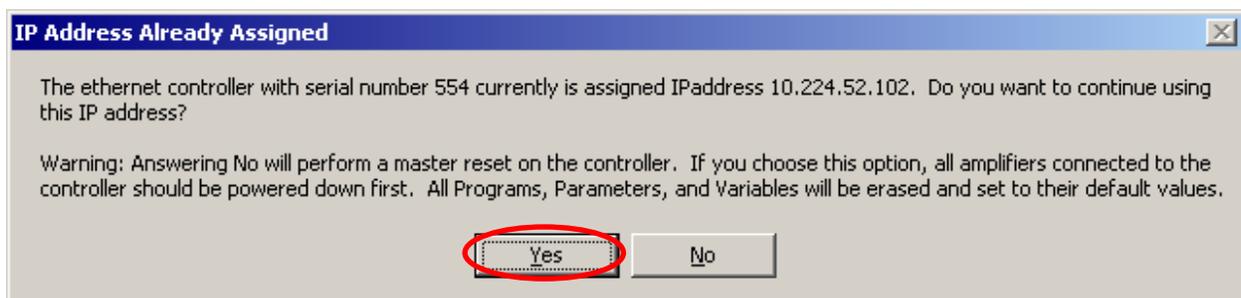Close the Controller Communications Parameters window.

Figure B.7. The "IP Address Already Assigned" message

3.13 Register the new IP address of the SPEED controller. Select Controller 2, the SPEED controller in the "Edit Registry" dialog box and repeat the steps outlined in 3.12 for this controller.

3.14 Finish with the controllers. Close the Edit Registry dialog, shut down the *DMC Smart Terminal* program, turn off the 24-volt power, and remove the Ethernet jumper cable.

4. Set the IP address of the machine-vision cameras and edit their host tables.

> DO NOT SAVE either camera program anytime during the process of setting IP addresses. IP addresses are saved separately in the camera, independent of the camera's program. The cameras of the benchmark profiler boot into an "online" state in which program parameters are changing, and they may not have the proper values for saving the program.

4.1 Run the Cognex *In-Sight Explorer* program using the shortcut icon on the DAS desktop. A screen similar to that shown in figure B.8 will appear.
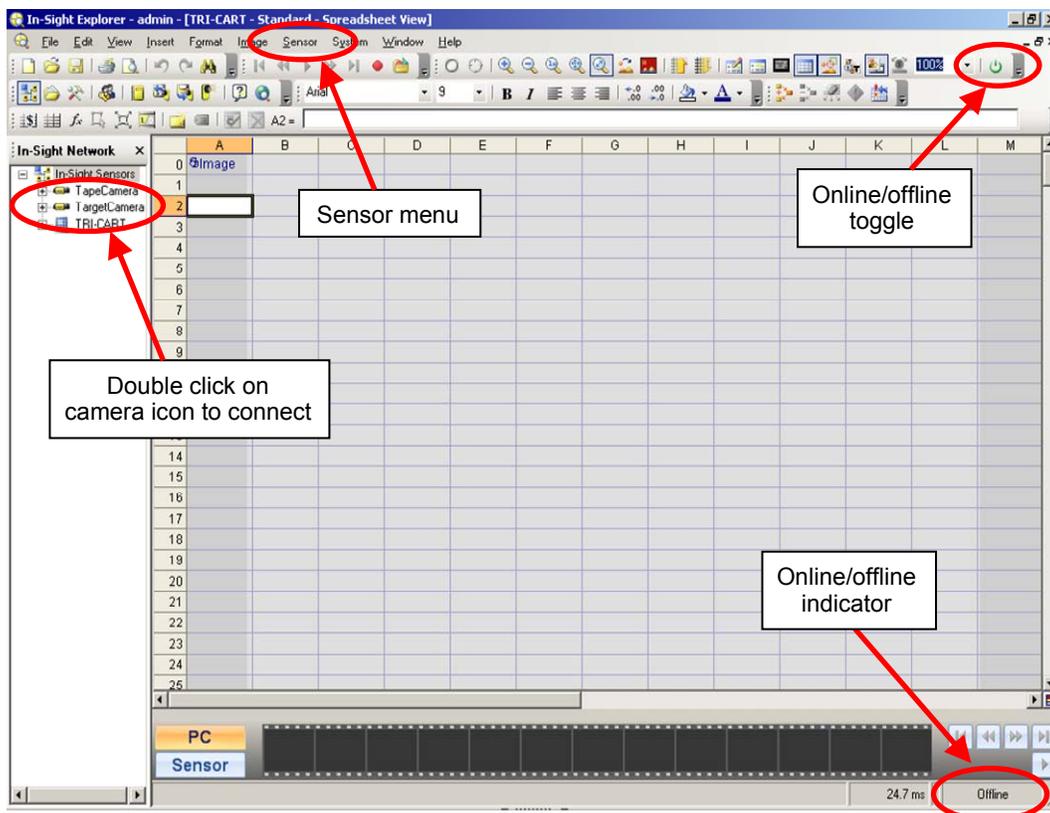
Figure B.8. *In-Sight Explorer* screen on start up (Spreadsheet view)

4.2 Connect to the TapeCamera and take it offline (figure B.8). In the Insight Network window on the left, double click on the TargetCamera icon. (If the camera icons are not visible, be sure the camera power is on, wait two or three minutes for the cameras to boot and click the Refresh button.) When the camera has connected, the online/offline indicator at the lower right will turn bright green and will read "Online." Click on the online/offline icon at the upper right and confirm that you want the camera offline. The indicator will turn gray and read "Offline."

4.3 Set the IP address (figures B.8 and B.9). Select "Network Settings..." from the Sensor menu. Enter the new IP address for the TapeCamera in the dialog box that appears. Alter the Subnet mask if that is appropriate. Click OK.

4.4 Edit the host table (figures B.8 and B.10). Select "Host Table..." from the Sensor menu. Select the tri-cart line and click on Edit. Enter the new IP address for the UMTRI DAS. Click OK in the editing window and then click OK in the dialog.

Figure B.9. The *Network Settings* dialog

4.5 Change the addresses of the TargetCamera. Repeat the steps described in 4.2 through 4.4, initially selecting, and connecting to, the TargetCamera rather than the TapeCamera.

4.6. Switch off the camera power.

5. Set the Internet Protocol (TCP/IP) information and edit the host table of the UMTRI DAS.

5.1 Set the Internet Protocol (TCP/IP) information of the UMTRI DAS.
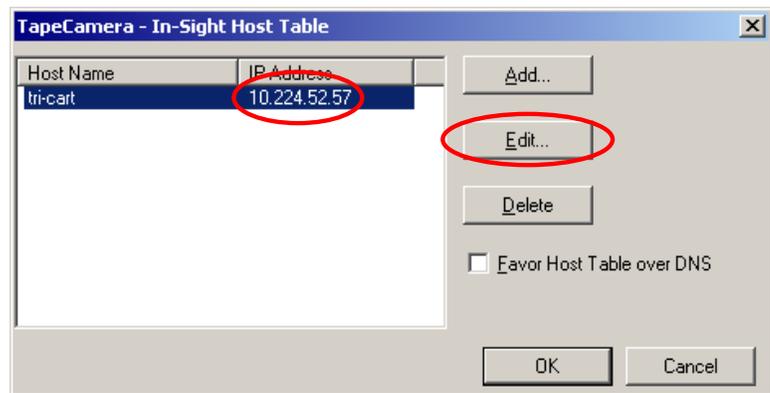
Figure B.10. The *Host Table* dialog

The operating system of the UMTRI DAS is Windows XP. The Internet Protocol (TCP/IP) information is set in the usual manner for such machines.

5.2 Edit the Host Table of the UMTRI DAS. The UMTRI DAS host table is contained in the file "host" located at C:\WINDOWS\system32\drivers\etc. Open the host file using *NotePad* (figure B.11). Update the IP addresses of the cameras and the controllers as appropriate. Change IP addresses only; do not change the device names. Save the file; be certain to maintain the name of the file as "host" with no extension.

Note that it is not strictly necessary for the two motor controllers to be identified in the DAS host table. They are not required for either the proper operation of the benchmark profile or for external communication with the controllers. These IP address have been included in the host table only for completeness.

Figure B.11. UMTRI DAS host file opened in *NotePad*

APPENDIX C.
TEST LOG — EXAMPLE SHEET

Date :_____   Test series:_____   Site:_____

| Section | Segment | | RunID | Passes | Time | | Compass | Comments |
	Number	Length			Start	End	Direction	

APPENDIX D.
CHANGING STORAGE BATTERIES

D.1. Introduction

The benchmark profiler is powered by four sealed, gelled-electrolyte, lead-acid batteries of the type commonly used on electric wheelchairs. These four batteries power two separate electrical systems. Two of the batteries are connected in parallel and provide 12-volt power for the profiler's instrumentation system, of which the DAS, the RoLine 1130, the two machine-vision cameras, and the drive-wheel encoder are the primary elements. The other two batteries provide a 24-volt power source for the motors of the profiler's drive and steering systems, and the LED light bars that illuminate the field of view of the TapeCamera. Through the action of a relay system, these two batteries are connect in series whenever the master switch of the 24-volt system is switched on, but they are connected in parallel with the other two batteries when the 24-volt system is switch off. This allows all four batteries to be charged simultaneously using either the 110-volt AC/12-volt DC charger or the special vehicle jumper cables provided.
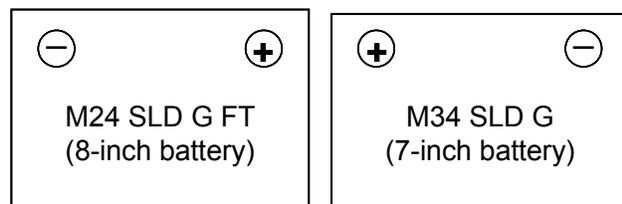
D.2. The Batteries

The four batteries supplied as original equipment on the benchmark profiler are all products of MK Battery. They are identified in table D.1. The batteries of the instrumentation system are slightly larger; they are about 1.2 in. taller and have about 1/3 greater energy-storage capacity. Because the difference in height is the most significant factor in changing batteries, the two types will be called the "8-in. battery" and the "7-in. battery" in this appendix, referring, respectively, to their nominal height.

<p align="center">Table D.1. Batteries of the benchmark profiler</p>

Profiler electrical system	MK Battery model	Rating	Dimensions
Instrumentation (12-volt)	M24 SLD G FT	63 ampere hour	10.2" x 6.80" x 8.24"
Motors (24-volt)	M34 SLD G	47.5 ampere hour	10.2" x 6.65" x 7.05"

The four batteries are carried in a rack slung under the main frame of the benchmark profiler. The 7-in. batteries for powering the motors are located on the left side of the profiler and the larger, 8-in. batteries of the instrument system are on the right side.

Except for their slight dimensional differences, the two battery types appear very similar. Take care to note, however, that the relative positions of the positive and negative terminals are reversed on the two types of batteries.

Figure D.1. Terminal positions differ on the two types of batteries used on the benchmark profiler

If it becomes necessary to replace any of the batteries of the benchmark profiler, it is strongly recommended that the same model batteries be used. In particular, the 7-in. height and flat-top terminal style of the two batteries of the 24-volt system are critical due to close clearance between the batteries and the LED light bars during removal and installation. The smaller style battery could also be used for the batteries of the 12-volt system, but the higher energy rating of the larger, recommended battery is advantageous.

D.3. Removing and Installing Batteries

Batteries are removed and installed from beneath the benchmark profiler. This requires the profiler to be lifted and secured 9-1/2 to 10 in. above its normal ride height. Specialized lifting hardware has been provided to allow lifting the profiler with an overhead crane or an appropriate floor crane (figure D.2). (With original-equipment batteries installed, but with the monitor and keyboard assembly and the cover removed, the profiler weighs 500 lbs.) If an appropriate crane is not available, the profiler may be lifted with three automotive floor jacks.

When changing batteries, do not loosen, or move in any way, the two, 2-in. square aluminum tubes that support the instrument kernel of the benchmark profiler (figure D.3).

Batteries may be removed and installed as described in the following steps.

1. Move the profiler to an appropriate work space. If an overhead crane is available for lifting, park the profiler centered under the crane.

2. Disconnect and remove the monitor and keyboard, and the joystick.

3. Remove the profiler's top cover. (This requires two people.) Lift the cover straight up until its lower edge clears the control panel. Set the cover aside.

4. Lift the profiler and support it securely with automotive jack
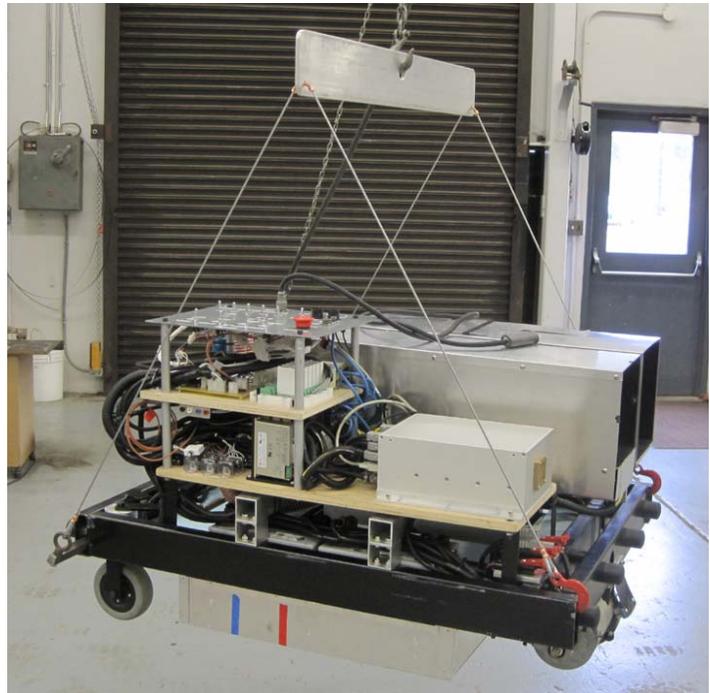

Figure D.2. The benchmark profiler suspended from an overhead crane using the special lifting hardware
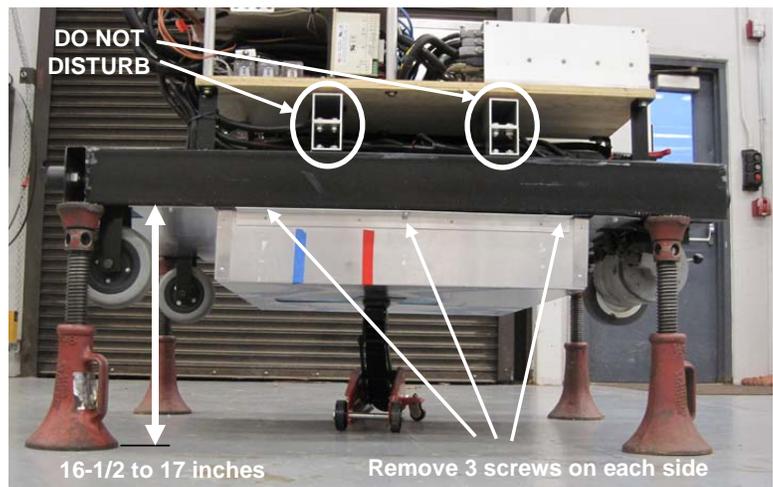

Figure D.3. The benchmark profiler supported on four post jacks with the battery jack lightly supporting the center floor panel

stands or other appropriate equipment such that the lower face of the main frame is between 16-1/2 and 17 in. above the work floor (figure D.3).

5. Remove the center floor panel of the profiler. The center panel is secured to the lower surface of the main frame with six screws, three on each side. Support the center floor panel <u>lightly</u> using the battery jack (figure D.3). Remove the six screws. Carefully lower the cover and remove it from the work area. (Two people working together, one on each side, can perform this task without using the jack.)

6. Working from the side of the profiler, disconnect the cables from the batteries to be replaced by removing the ¼-in. machine screws from the terminals. Set the screws aside; do not replace them in the terminal. Cover the terminals with insulating tape such as duct tape.

7. Remove the battery tie-downs of the batteries to be replaced (figure D.4). Remove the nuts from the top of the threaded rods. Remove the rods from the bottom of the frame. Slide the flat bar out toward the front of the profiler.

8. Remove the plate that forms the inner lip of the battery rack for the batteries to be replaced (figure D.4). This can be done either by reaching into the battery area from the front edge or by working from underneath.

9. Remove all batteries to be replaced. See figure D.5 and the following detailed instructions.
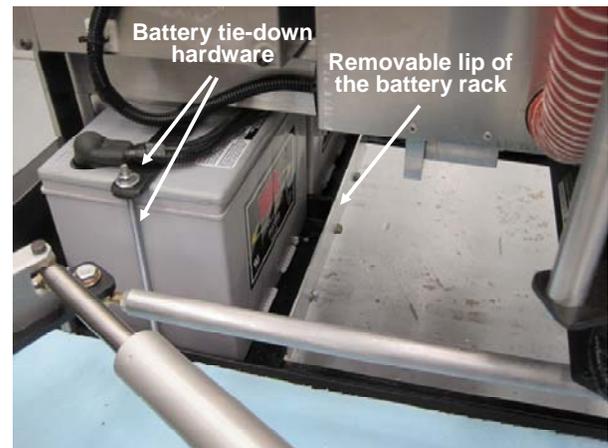
Figure D.4. View of the batteries on the right side (8-in., 12-volt system) looking from the front

    For each battery to be removed:

   Position the battery jack crosswise beneath the profiler and raise it to a position so that the support plate is adjacent to the battery to be removed and at a height placing the plate just above the studs for the side lip of the rack (figure D.5.a). This will result in the surface of the support plate being at or slightly lower then the bottom of the battery as it sits in the battery rack.

    Slide the battery out of the rack and onto the jack (figure D.5.b). Maneuver the jack so that the battery is clear of the studs used to retain the removable lip of the rack (figure D.5.c). Take care to avoid contact between the battery and the LED light bars, especially when working with the batteries that are carried on the left side of the profiler.

    Lower the jack, with the battery, to its lowest position. Remove the jack handle and rotate the jack 90 degrees. Replace the handle and remove the jack and battery toward the front of the profiler (figure D.5.d).

10. Install the new batteries. After all batteries to be replaced have been removed, install the new batteries. For each replacement battery, reverse the process described in step 9. During the installation process, cover the terminals of the batteries with insulating tape.
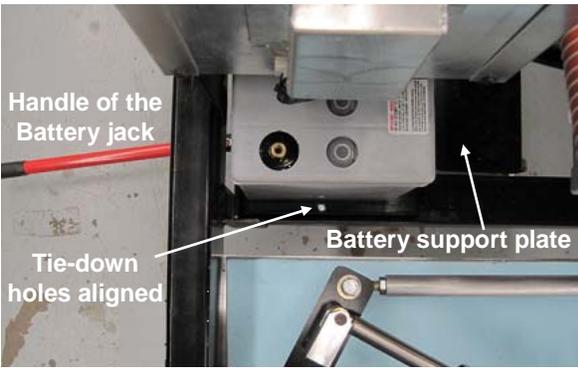
a. Position the battery jack with the support plate
   adjacent to the battery to be removed.

b. Slide the battery onto the support plate.
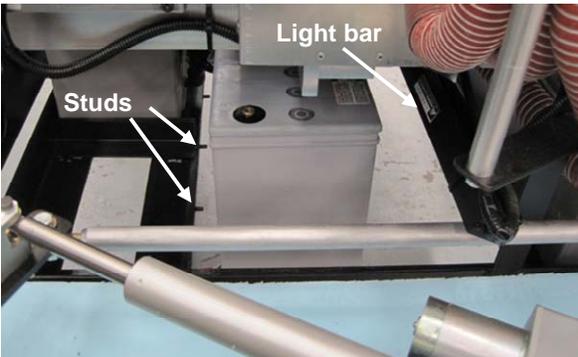
c. Take care that the battery is clear of the light
   bar and the studs; lower the battery jack.
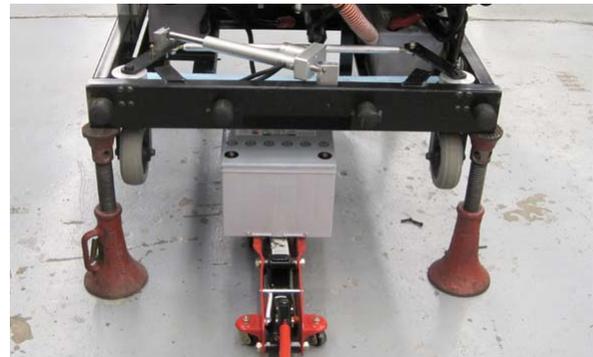
d. Rotate the jack 90 degrees and remove it and
   the battery toward the front of the profiler.

Figure D.5. Removing a battery

11. After all new batteries are in place in the rack, reverse the process described in steps 1 through 8. Note that the left- and right-side battery racks can each slide on the cross members that support them. The racks are held in place by the tie-down rods. Be sure that the racks are positioned so that the holes for the tie-down rods in the rack and in the cross member are aligned (figure D.5.a).

APPENEDIX E.
MAKING AND INSTALLING TRAINED PATTERNS
OF OTHER GUIDANCE TAPES

E.1. Introduction

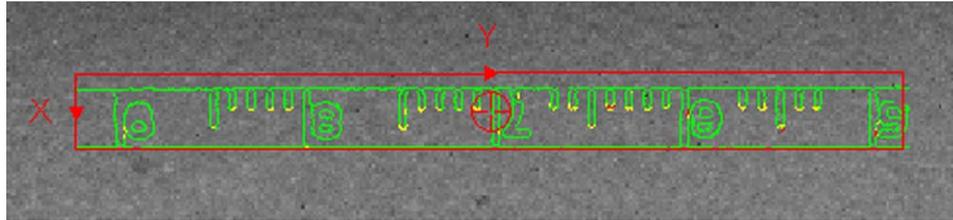The guidance system of the benchmark profiler, as of August 31, 2012, is configured to follow a Keson Model NRS10300H nylon-coated steel tape. That is, the active guidance program, *Guidance.current.job*, of the *TapeCamera* includes a *trained pattern* that is an image of a section of this model tape.

As delivered, the memory of *TapeCamera* contains three programs:

• *Guidance.current.job* — The afore-mentioned *In-Sight Explorer* spreadsheet program that is the active guidance-control program of the benchmark profiler. Using this program, the *TapeCamera* computer, coupled with the DAS computer, controls the automatic steering of the benchmark profiler that allows it to follow the guidance tape.

• *Guidance.UMTRI.v1.1.job* — An *In-Sight Explorer* spreadsheet program whose content is identical to *Guidance.current.job* as of August 31, 2012, and is primarily intend for backup.

• *TapeTrainedPatterns.job* — A short, *In-Sight Explorer* spreadsheet (figure E.1) that contains two different trained patterns of guidance tapes prepared by UMTRI. These two patterns are in cells A4 and A6, respectively (figure E.2).

Figure E.1. *TapeTrainedPatterns.job* spreadsheet

a. Trained pattern image of a Keson Model NR10200 tape
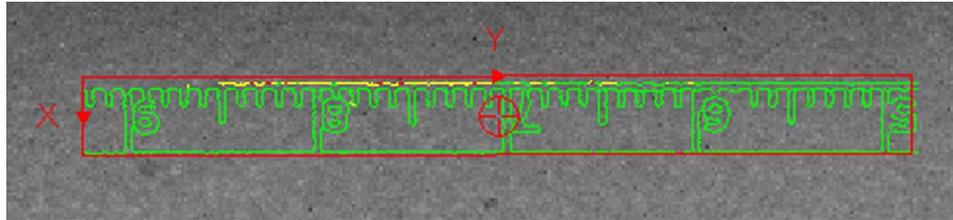
b. Trained pattern image of a Keson Model NRS10300H tape

Figure E.2. Trained pattern images contained in *TapeTrainedPatterns.job*

The pattern in cell A4 of *TapeTrainedPatterns.job* is based on an image of a section of a Keson Model NR10200 tape (figure E.2.a). This tape is 200 ft. long and 0.39 in. wide. The pattern in cell A6 is based on an image of a section of a Keson Model NRS10300H tape (figure E.2.b). This tape is 300 ft. long and 0.42 in. wide. Both of these tapes are marked off in feet with subdivisions of 0.1 ft. and 0.01 ft. The pattern in cell A6 of *TapeTrainedPatterns.job* is identical to the pattern in *Guidance.UMTRI.v1.1.job* and in *Guidance.current.job* as delivered.

In both cases, the patterns derive from a section of tape that is about 0.45 ft. long and ranges from x.48 ft. to x.93 ft. (where x may vary from 0 to 299). This section of the tape is used because the markings in this range repeat identically for each foot of the tape, i.e., they include no indication of the current foot or any other marking that changes along the length of the tape.

One used and two brand new Keson Model NRS10300H tapes were delivered with the benchmark profiler. With reasonable care, these tapes should be sufficient for use with the profiler for some time to come. But, of course, they will not last indefinitely. When it becomes necessary to obtain new tapes for use with the profiler, we strongly recommend continuing to use the Model NRS10300H (assuming, of course, that the design and, especially the appearance, of this model tape remains exactly as current in 2010). If, however, it becomes necessary to use a guidance tape with a different appearance then the NRS10300H or the NR10200, it will be necessary to create a new trained pattern, based on the new tape, for use in the active guidance-system program in the camera's memory. The *TapeTrainedPatterns.job* program is provided to aid in the creation of new trained patterns.

When selecting new tapes for use with the profiler, it is very desirable that the tapes' pattern be similar to those of the Keson tapes with regard to the following four criteria:
*   the tape measurements be in feet,
*   the subdivisions be in 0.1 ft. and 0.01 ft.,
*   the tape be less than 0.5 in. wide, and
*   the image from x.48 ft. to x.93 ft. repeat identically for each foot of the tape.

If these four criteria can not be met, it is nevertheless mandatory that some range of the pattern, approximately 0.45 ft. in length, repeats identically each foot along the tape. Moreover, it will be necessary to change several of the parameters in the guidance-control program depending on the particulars of the tape. If it becomes necessary to use a tape that varies from these criteria, UMTRI should be contacted.

Section E.2 describes how to make a new trained pattern from a guidance tape that meets these four criteria using *TapeTrainedPatterns.job*. Section E.3 describes how to modify *Guidance.current.job* to use the new trained pattern.[13]

E.2. Creating a New Trained Pattern from the Image of a Guidance Tape

Locate the benchmark profiler on a clean, dry, smooth, level, non-reflective surface of a neutral color. Position the profiler to allow for clear access to both the front and rear of the profiler. Follow the steps below to create a trained pattern with the image of a new guidance tape.

E.2.1. Power On

Shut down the 24-volt master and, if on, shut down the 12-volt system also.

Unplug and remove the joystick and the monitor and keyboard. Remove the cover. On the secondary control panel, set the switches for the two servo control systems to abort and the switch for the TargetCamera to off. Leave the switch for the TapeCamera on.

Replace the cover and reconnect the monitor and keyboard.

Turn on the 24-volt master, the 12-volt main power, and the camera power.

E.2.2. Execute In-Sight Explorer and Select the Tape Camera

When the DAS has booted, start the Cognex, *In-Sight Explorer* program on the DAS by clicking its short-cut icon on the desktop. The program will initiate in the *Spreadsheet* viewing mode. In the panel at the left, double click on the *TapeCamera* icon to connect to that camera. If the *TapeCamera* icon is not present, it is most likely that the camera has not yet completed its own boot process. Wait a moment and click the *Refresh* button.

E.2.3. Take the Camera Off Line.

After connecting to the TapeCamera, the *Spreadsheet* program will appear and the online/offline indicator at the lower right will appear bright green and read "Online". Take the program offline by clicking on the *Online/Offline* toggle icon

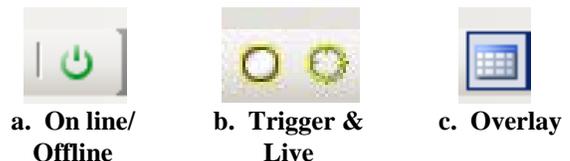a. On line/ b. Trigger & c. Overlay
   Offline   Live

Figure E.3. Control-bar icons of interest
(Also see figure B.8.)

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[13] It is possible to combine these steps, creating the new trained pattern using *Guidance.current.job*, but this is not recommended. Rather, using *TapeTrainedPatterns.job* provides a good means of documenting and archiving all the trained patterns that may be created.

(figure E.3.a) at the right end of the control bar. (Or, under the *Sensor* menu, select *Off line*, or press Ctrl+F8.) In the dialog box that appears, answer *Yes* to "Are you sure you want to go offline?"

E.2.4. Open the TapeTrainedPatterns.job

Under the *File* menu, select *Open Job* (or press Ctrl+O). The dialog box that appears will show a list of the programs in the camera memory ("Look in: ▮▭▮TapeCamera" will be indicated.). Select *TapeTrainedPatterns.job* (or a more recent variant there of; see section E.2.5) and click the *Open* button. Cells A0 through C6, excepting A4 and A6, of this spreadsheet are locked and the sheet is protected.[14] All other cells are unlocked

E.2.5. Save the Spreadsheet Under a New Name

This step is not mandatory, but is strongly suggested if the program that has just been opened is the original *TapeTrainedPatterns.job*.

Under the *File* menu, select *Save Job As*. The dialog box that opens will list the programs in the camera memory. The new spreadsheet program can be saved here and/or in the DAS memory.[15] Select the place you wish to save the program, type in the new name and click save.[16]

E.2.6. Select and Copy the Appropriate Pattern

Select the spreadsheet cell containing the existing trained pattern that best matches the new tape being used. (Cell A4 contains the pattern from the Keson tape that is 0.39 in. wide. Cell A6 contains the pattern from the Keson tape that is 0.42 in. wide. Other cells in the A column may contain patterns created with other tapes.) Copy this cell and paste it into the first available appropriate cell below (cell A10 or A14 or A18, etc.).

E.2.7. Create and View a New Image in the Duplicated Trained Pattern

Select the spreadsheet cell with the duplicate pattern just created, and trigger the camera to take a "blank" image (i.e., an image of the clean floor beneath the profiler). To trigger the camera, click on the *Trigger* icon in the control bar (the left-hand image in figure E.3.b). (Or open the *Image* menu and select *Trigger,* or press F5). A new image of the floor should appear with the selected trained pattern superimposed on its center (similar to figure E.1).

Now remove the overlay of the spreadsheet to get a clear view of the image and trained pattern. Click on the *Overlay* icon in the control bar (figure E.3.c). (Or select *Overlay* under the *View* menu or

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[14] This spreadsheet, as is the case with all the speadsheets provided in the TargetCamera and TapeCamera, is protected but without password. That is, these sheets may be unprotected under the file menu without entering a password.

[15] Note that files stored in the camera memory can not be easily deleted using *In-Sight Explorer*. Deleting files from the camera is accomplished via telnet communications. See section E.4.

[16] One suggestion is that the new spreadsheet be named *NewTapeTrainedPatterns.job*. and be saved to both camera and DAS memory. This program may then be used to create any and all new trained patterns, always being saved under the same name. This approach will avoid creating many new programs in the camera's memory, but will maintain the original *TapeTrainedPatterns.job* in the camera as a backup.

press Shift-F6.) The overlay of the spread sheet will disappear leaving a clearer view of the camera image and trained pattern (figure E.4).
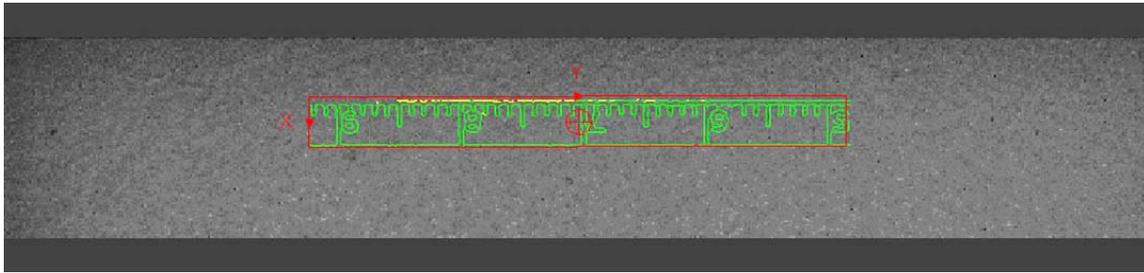
Figure E.4. A "blank" image with a trained pattern superimposed without an overlay of the spreadsheet

E.2.8. Position the New Tape

Positioning the tape is best done with two or three people. One person operates the Insight-Explorer program, taking images of the tape and directing its repositioning. Two people position the tape at the front and rear of the profiler, respectively. One person can fill the roles of the program operator and th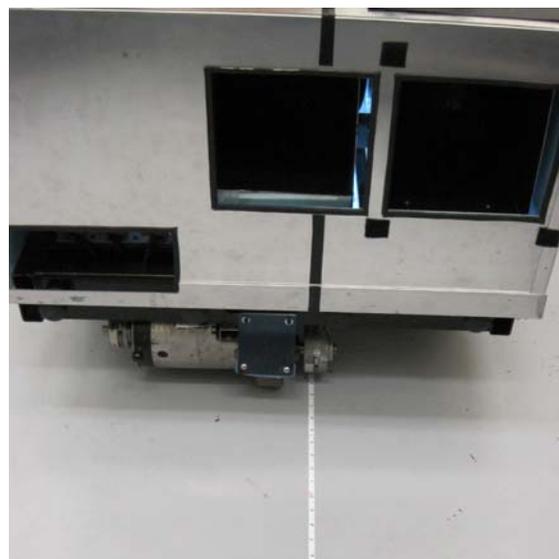e positioner at the rear of the profiler. Alternatively, the job can be done by just one person who performs all the tasks and anchors the tape in position using tape weights.

Initially, unroll several feet of the new guidance tape and position the tape under the benchmark profiler with the zero-end of the tape extending out from under the rear of the profiler and the reel end in front of the profiler. At each end of the profiler, position the tape so that it is on the floor, directly below the vertical, black-tape strips on the front and rear faces of the cover (figure E.5). Stretch the tape moderately taught in this position.

a. **View of the tape from in front of the profiler**   b. **View of the tape from behind the profiler**

Figure E.5. The guidance tape positioned beneath the profiler aligned with the vertical black-tape stripes

During the process of locating the tape, in addition to the specific steps described below, it may be helpful to observe the tape position in *live video*. To do so, click on the *Live video* icon in the tool bar (the right-hand icon in figure E.3.b). The trained image will disappear and a continuous live view

of the TapeCamera field of view will appear. The tape should be positioned to appear straight and near center in this view. Click again on the *Live video* icon and the live video will stop and the trained image will reappear.

Trigger the camera to take a single image of the tape and observe the position of the tape relative to the trained image. The tape may initially be poorly aligned in all three dimensions, i.e., longitudinally, laterally and angularly (figure E.6).
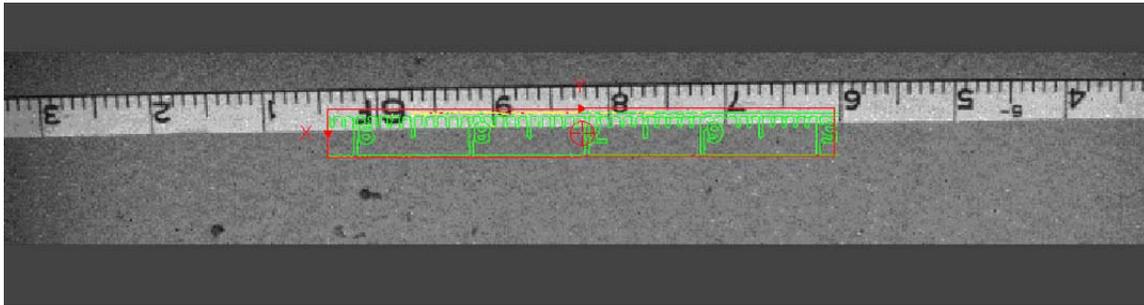
Figure E.6. Initial image with the tape poorly aligned longitudinally, laterally and angularly

The program operator, having observed the position of the tape, now directs the re positioning of the tape to improve its alignment with the pattern. The program operator then takes another image to see the new position. The process is repeated, likely many times, until the tape is <u>very</u> well aligned with the existing trained pattern (figure E.7).

Figure E.7. Final image with the tape very well aligned with the existing trained pattern

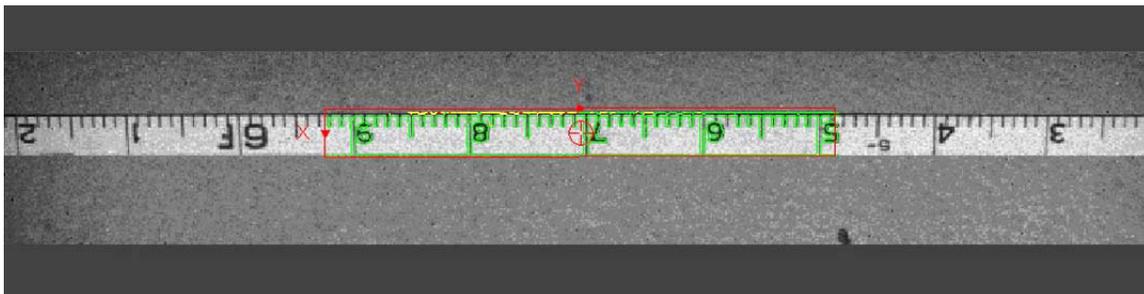Typically, it is most efficient to address the longitudinal position of the tape as the first step in this process. (This can be done as well by moving the profiler as by moving the tape.) Then proceed with the lateral and angular alignment (which typically take place simultaneously) and minor readjustments of the longitudinal position. The positioners should be aware that the position of the tape under the camera is sensitive not only to their positioning longitudinally and laterally, but also to small amounts of local "twist" that they may inadvertently put into the tape.

Once the tape is properly positioned, anchor it in place with foam-block weights so that it is no longer subject to moving. Take one more image to insure that the tape is still in the proper position. Readjust if the tape has moved.

E.2.9. Create the New Trained Pattern

The tape is now in the proper position to be used to create a new trained pattern.

Bring back the spreadsheet overlay by clicking on the *Overlay* icon in the control bar (figure E.3.c). (Or select *Overlay* under the *View* menu or press Shift-F6.) Now double click on the cell with the newly created duplicate trained pattern. A dialog box will open that contains all the parameters used to create the previously existing trained pattern. Do not change any parameters, as the new trained pattern should be created in just the same way. Click on the *OK* button and the new trained pattern will be created.

E.2.10. Save the Spreadsheet Program

Save the spreadsheet program containing the new trained pattern in the camera and/or the DAS memory. (See the discussion in section E.2.5 on saving the spreadsheet under a new name.)

E.2.11. Power Down.

The 24-volt system may now be turned off.

If the new trained pattern is to be inserted into the guidance program immediately, proceed to section E.3. Otherwise, shut off the camera power, shut down the DAS, turn off the 12-volt main power and reverse the process described in section E.2.1 to reconfigure the switches on the secondary control panel in the standard configuration.

E.3. Inserting a New Trained Pattern into the Guidance Program

The TapeCamera is programmed to execute the program *Guidance.current.job* and to place itself online when it boots up. This section describes how to insert a new trained pattern into that program file. It is also suggested that comment fields in the program be edited appropriately to document the modification. The modified program can then be saved to camera memory without changing its name. However, it is also suggested that the new version be saved elsewhere with an appropriate version identification in the file name.

Inserting a new trained pattern into *Guidance.current.job* is a straightforward matter of copying and pasting the appropriate spreadsheet cells from the trained-patterns spreadsheet to the guidance-control spreadsheet and editing the appropriate comment cells in the guidance-control spreadsheet.

E.3.1. Power Up and Initiate Programming

If beginning a new work session, power up the DAS and the cameras. Start the *In-Sight Explorer* program. Select the TapeCamera and take the guidance program offline according to the instructions of section E.2.1, E.2.2, and E.2.3.

E.3.2. Copy the New Trained Pattern

Use the *In-Sight Explorer* to open the version of the *TapeTrainedPatterns.job* spreadsheet (see section E.2.4) that contains the new trained pattern to be inserted in the guidance-control program. Select the cell containing the new trained pattern to be used and copy the cell (*Copy* in the *Edit* menu or Ctrl-c).

E.3.3. *Open the Current Guidance-Control Program and Insert the New Trained Pattern*

Now open *Guidance.current.job* from the *TapeCamera* memory.

All the cells of this spreadsheet program are lock, except as listed below, and the spreadsheet is protected.[17]

- *L0 through L3* — Four comment fields identifying the program, its creation date and identifying features.
- *A21* — Cell containing the trained pattern of the guidance tape image.
- *C21* — A comment field identifying the guidance tape used to produce the trained pattern.

Select cell A21 and paste in the trained pattern that was copied in section E.3.2 (*Paste* in the *Edit* menu or Ctrl-v).

Edit the comment fields in cells L0 through L3 and in cell C21 as appropriate. Note that the text of comments must begin with an apostrophe (').

E.3.4. *Insure that the Cognex Count is Zero*

Cell H10 of the *Guidance.current.job* spreadsheet contains an integer variable designated as "Cognex Count" as indicated by the comment field in cell H9. This integer variable increments by 1 each time a new image is taken by the program.

Cell G9 contains a checkbox labeled "Reset Cognex Count." When the box is checked, the value of Cognex Count is forced to zero. Unchecking the box allows Cognex Count to be incremented.

- <u>The value of Cognex Count in cell H10 must be "0" when the program becomes active upon booting up the benchmark profiler.</u>
- <u>Therefore, the value of Cognex Count in cell H10 must be "0" and the check box at cell G9 must NOT be checked whenever the program is saved to memory.</u>

To reset the Cognex Count in H10 to "0", click on G9 causing the check mark to appear, which, in turn, will cause the value in H10 to reset to "0". Immediately click on G9 again causing the check mark to disappear. The program is now ready to be saved to memory.

E.3.5. *Save the Modified Version of Guidance.current.job*

Save the modified version of *Guidance.current.job* to the camera memory using *Save Job* (Ctrl-s) from the *File* menu.

It is also strongly suggested that a backup copy of the new, modified version of *Guidance.current.job* be saved to memory in the DAS or elsewhere under a name indicating the version ID, e.g., *Guidance.rev_x.job*.

---

[17] This spreadsheet, as is the case with all the speadsheets provided in the TargetCamera and TapeCamera, is protected but without password. That is, these sheets may be unprotected under the file menu without entering a password.

E.3.6. Power down and Reset the Secondary Control Panel Switches

The 24-volt system may now be turned off. Shut off the camera power, shut down the DAS, turn off the 12-volt main power and reverse the process described in section E.2.1 to reconfigure the switches on the secondary control panel in the standard configuration.

E.4. Deleting Files from Camera Memory

While files can be saved to memory in either the TapeCamera or the TargetCamera using *In-Sight Explorer*, files can not be deleted from camera memory using this program. Files can be deleted from memory of either of the cameras by accessing the camera using telnet and using the *Basic Native Mode* command for deleting files (df).

Turn on the 12-volt power and the camera power. Once Windows has booted, run *In-Sight Explorer* using the shortcut icon on the desk top. Connect to the camera of interest and take it offline (see sections E.2.2 and E.2.3).

Return to the Windows desktop and select *Run...* from the *Start* menu. Enter "telnet" followed by a space and the IP address of the camera of interest.[18] When prompted, enter "admin" for the password and make no entry (except a carriage return) for the password.

To delete a file enter "df" followed by the exact file name (including the ".job" suffix) with no intervening space. Following this entry, one of the following coded responses will be returned from the camera:

     1   The command was executed successfully.
     0   Unrecognized command.
   -1   The filename is missing.
   -2   The file could not be deleted, the sensor is Online, a file does not exist with the given name, or the job data is invalid, therefore the command could not be executed.
   -6   User does not have Full Access to execute the command.

When the file(s) is (are) successfully deleted, close the telnet window.

You can confirm that the job file of interest was deleted by returning to *In-Sight Explorer* and selecting "Open job..." from the *File* menu. The deleted job file will no longer appear in the listing.

Additional instructions and examples are provided by Cognex in *In-Sight Explorer Help*. Under the *Help* menu in *In-Sight Explorer*, select *In-Sight Explorer Help*. On the left of the screen, select the *Index* tab. Scroll down the listing and double click on *Delete File*.

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[18] As delivered, the IP addresses are 10.224.52.100 for the TargetCamera and 10.224.52.101 for the TapeCamera.

APPENEDIX F.
SCHEMATIC AND WIRING DIAGRAMS

F.1. Annotated List of Figures

F.1.1. Schematic diagrams

F.1. Locations of electrical components
- a. Major elements in the plan view
- b. Upper instrument shelf
- c. Lower instrument shelf

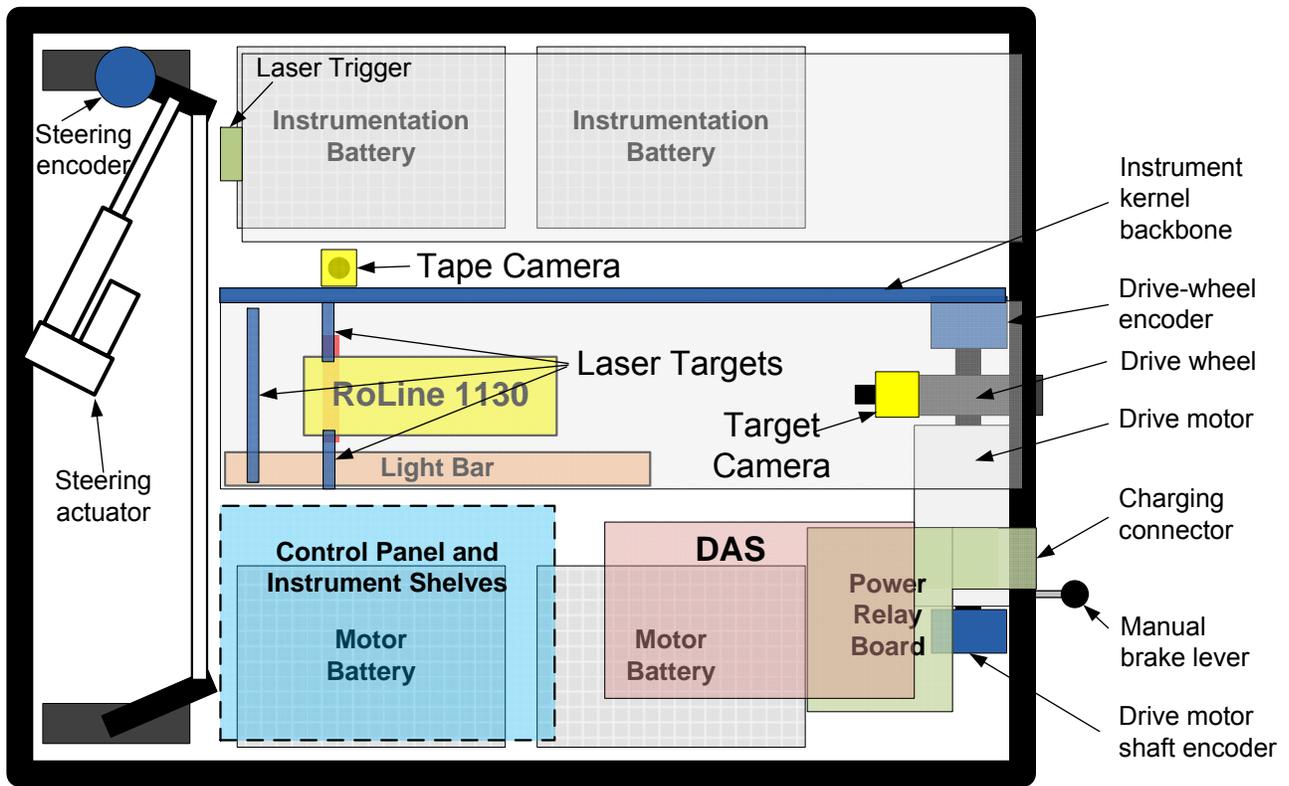F.2. Block diagram of the electrical systems

F.1.2. Wiring Diagrams

<u>Interconnect wiring</u>

F.3. Cart – Servo Drive
Steering actuator, drive motor, servo controllers, servo amplifier.

F.4. Cart – Operator Interface
Main control panel, sub control panel, and joystick.

F.5. Cart – Analog Isolation
Isolation modules between instrumentation and servos.

F.6. Cart – DAS connectors|
Connectors from DAS to isolation modules, operator interface, cameras, RoLine, power board, laser trigger, and drive wheel encoder.

F.7. Cart – Power and interconnect
Batteries, PoE modules, light bar, fans, and connections to power relay board, servo drives, DAS, laser trigger, and Ethernet switches.

<u>Circuit-board wiring</u>

F.8. Cart – Power board
Contains relays for servo command signals, relays for DAS and sensor power, DCDC converters for cameras and RoLine, regulators for isolation modules and Ethernet switch for servo controllers.

F.9. Cart – Power relay board
Contains relays to switch between charging and operation modes for 24V equipment and provides interface between charger and batteries.

F.10. Rotating laser timing sensor
Part of Laser Trigger assembly on cart. Detects arrival of laser dot at cart and generates trigger pulses for DAS and target camera.

F.11. Rotating laser timing control

Mounted in laser alignment head. Maintains stable laser turret speed.

F.12. Cart – DAS Interface Board; 1 of 2

Internal to DAS. Provides isolation and signal conditioning for triggers and timing signals.

F.13. Cart – DAS Interface Board; 2 of 2

Same.

F.14. Cart – DAS Internal Wiring; 1 of 2

Internal to DAS. Shows wiring between DAS external connectors and DAS interface board, A/D card, and counter/timer card.

F.15. Cart – DAS Internal Wiring; 2 of 2

Same.

F.16. Cart – DAS Power Input Filters

Internal to DAS. Noise reduction for DAS internal power supplies.

F.17. Cart – Signal Schematics; 1 of 3

Shows signal routing independent of physical location and connectors.

F.18. Cart – Signal Schematics; 2 of 3

Same.

F.19. Cart – Signal Schematics; 3 of 3

Same.

a. Major elements in the plan view
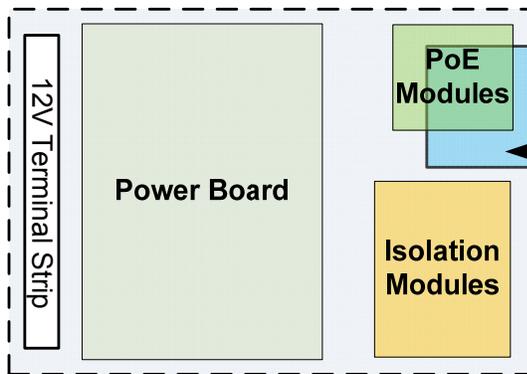
b. Upper instrument shelf
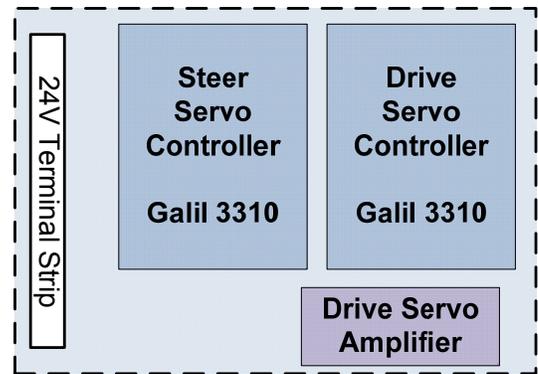
c. Lower instrument shelf

Figure F.1.   Locations of electrical components

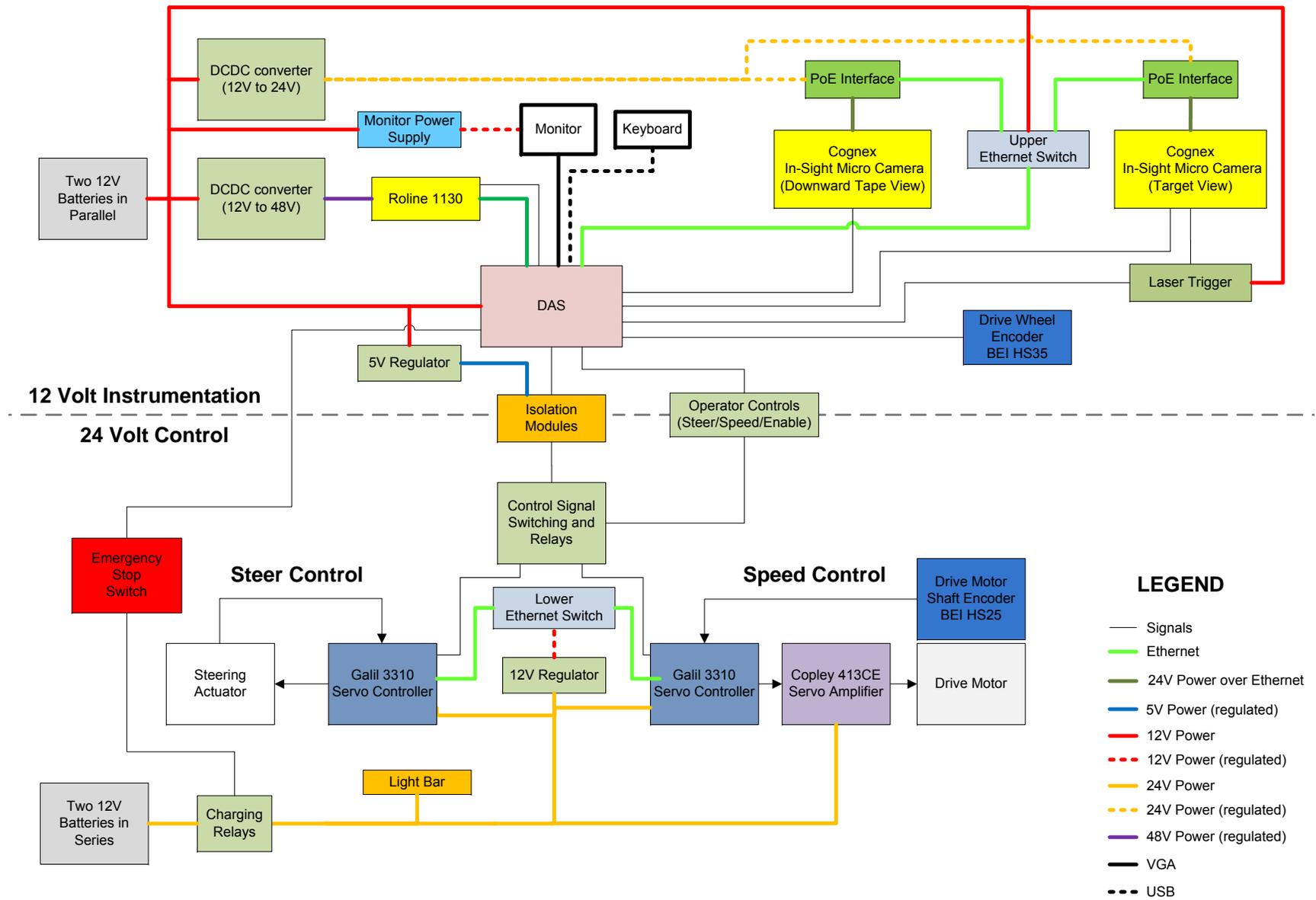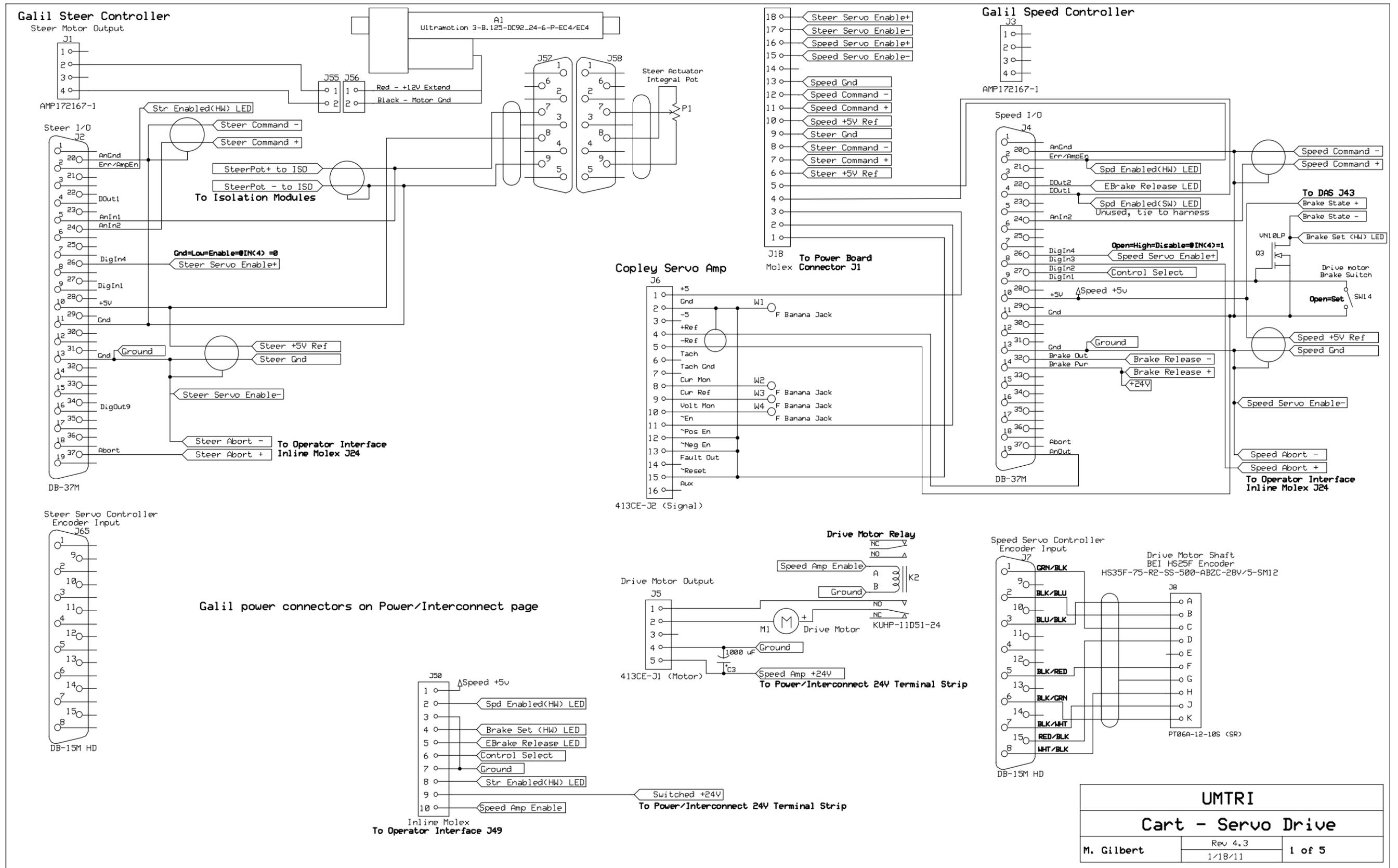**Figure F.2. Block diagram of the electrical systems**

Figure F.3. Cart – Servo drive
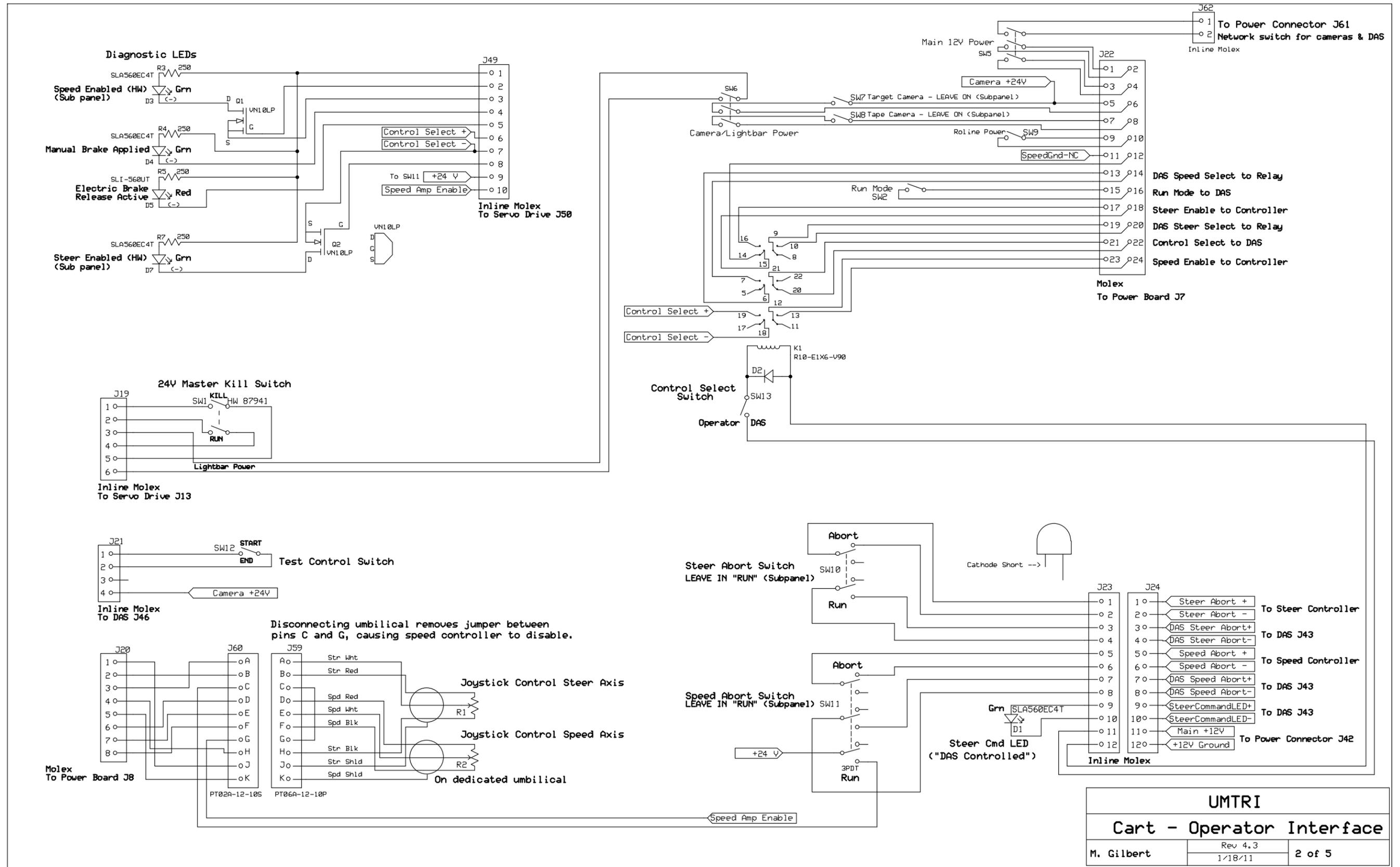
Figure F.4. Cart – Operator interface

To Steer Servo J57

SteerPot + to ISO
SteerPot - to ISO

DataForth
5B41
N/C Vout
+In I/O Com
-In Rd EN\
N/C +5V
CH0 Pwr Com
U1 **5B41-02**

SteerPot +
SteerPot -

DataForth
5B49
N/C Vin
+Out I/O Com
-Out Wr EN\
N/C +5V
CH1 Pwr Com
U5 **5B49-02**

SpeedOut+
SpeedOut-

J25
1 o
2 o
3 o
4 o
5 o
6 o
7 o
8 o
9 o
10 o
11 o
12 o
Molex
To Power Board J6

DAS Speed Cmd
Joystick Speed Cmd
DAS Steer Cmd
Joystick Steer Cmd

DataForth
5B41
N/C Vout
+In I/O Com
-In Rd EN\
N/C +5V
CH2 Pwr Com
U3 **5B41-02**

OperatorSpeedCmd +
OperatorSpeedCmd -

DataForth
5B49
N/C Vin
+Out I/O Com
-Out Wr EN\
N/C +5V
CH3 Pwr Com
U4 **5B49-02**

SteerOut+
SteerOut-

DataForth
5B41
N/C Vout
+In I/O Com
-In Rd EN\
N/C +5V
CH4 Pwr Com
U2 **5B41-02**

OperatorSteerCmd +
OperatorSteerCmd -

+5 Volt Supply
ISO Gnd
To Power Board J3 Pins 9 and 10

To Power/Interconnect 24V Terminal Strip
+24 V
Ground

DataForth
5B41
N/C Vout
+In I/O Com
-In Rd EN\
N/C +5V
CH5 Pwr Com
U2 **5B41-09**

Motor Supply +   24V Battery Monitor
Motor Supply -   To DAS connector J45

To DAS Connector J30

UMTRI
Cart – Analog Isolation
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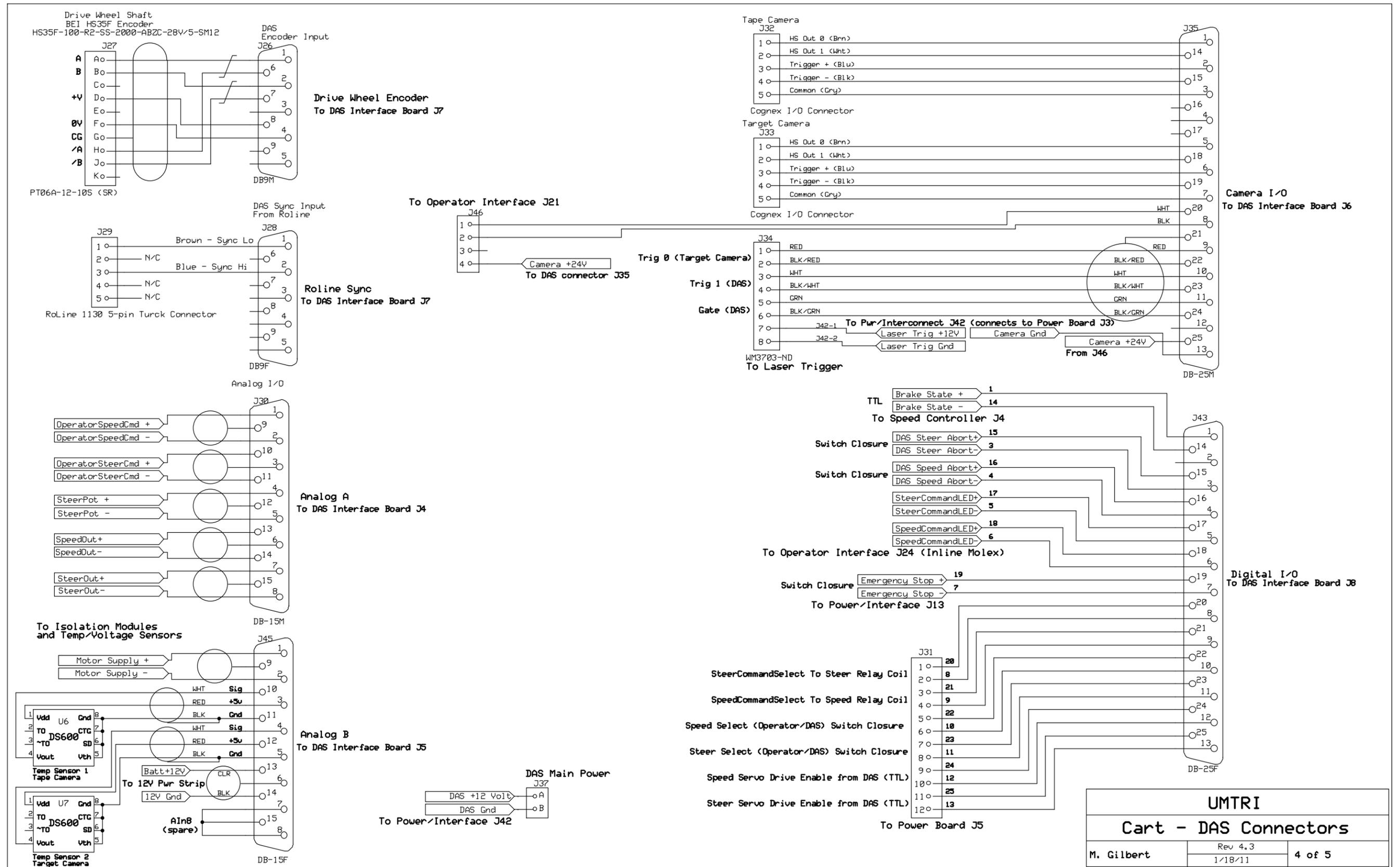1/18/11

Figure F.5. Cart – Analog isolation

Figure F.6. Cart – DAS connectors
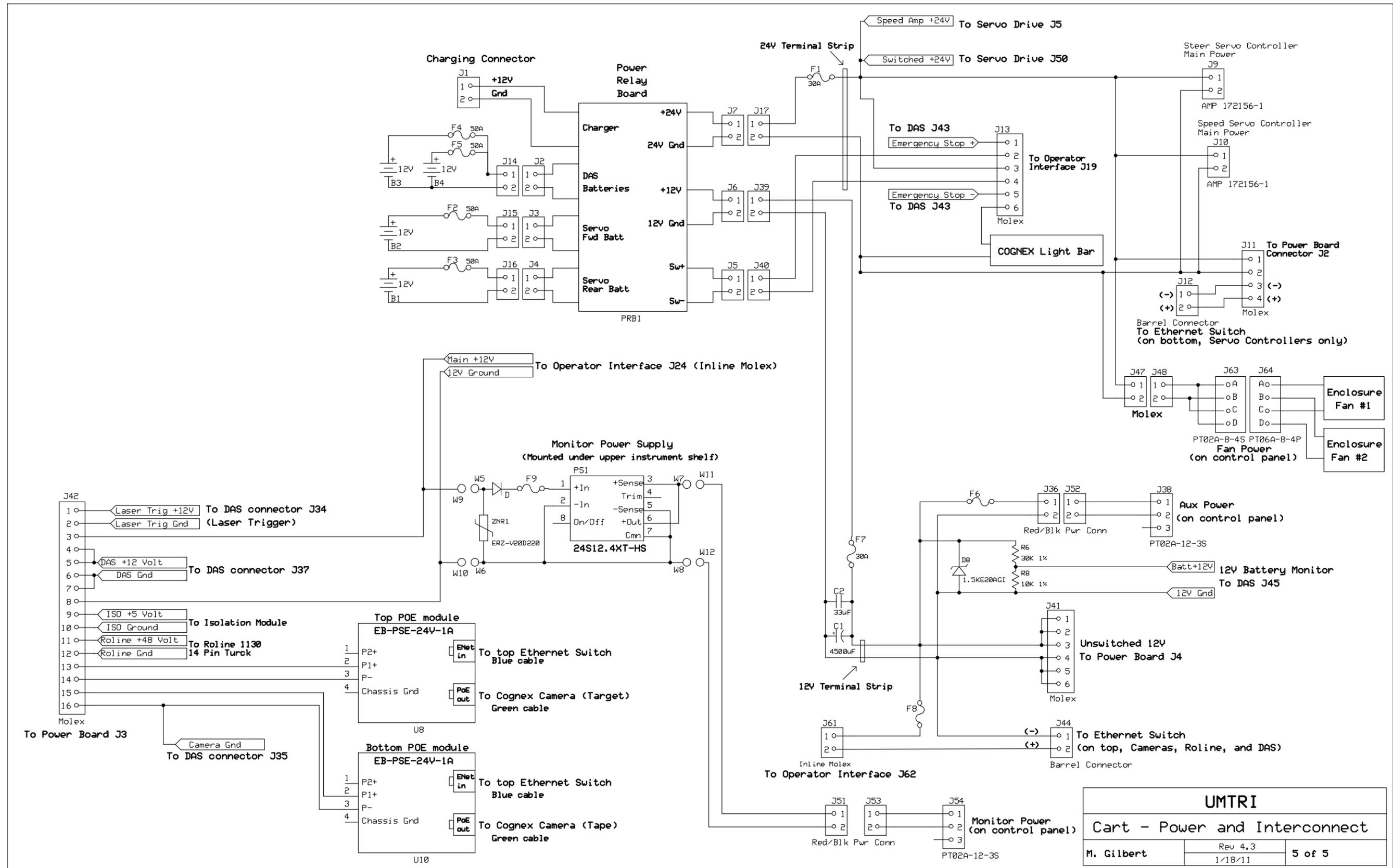
Figure F.7. Cart – Power and interconnect
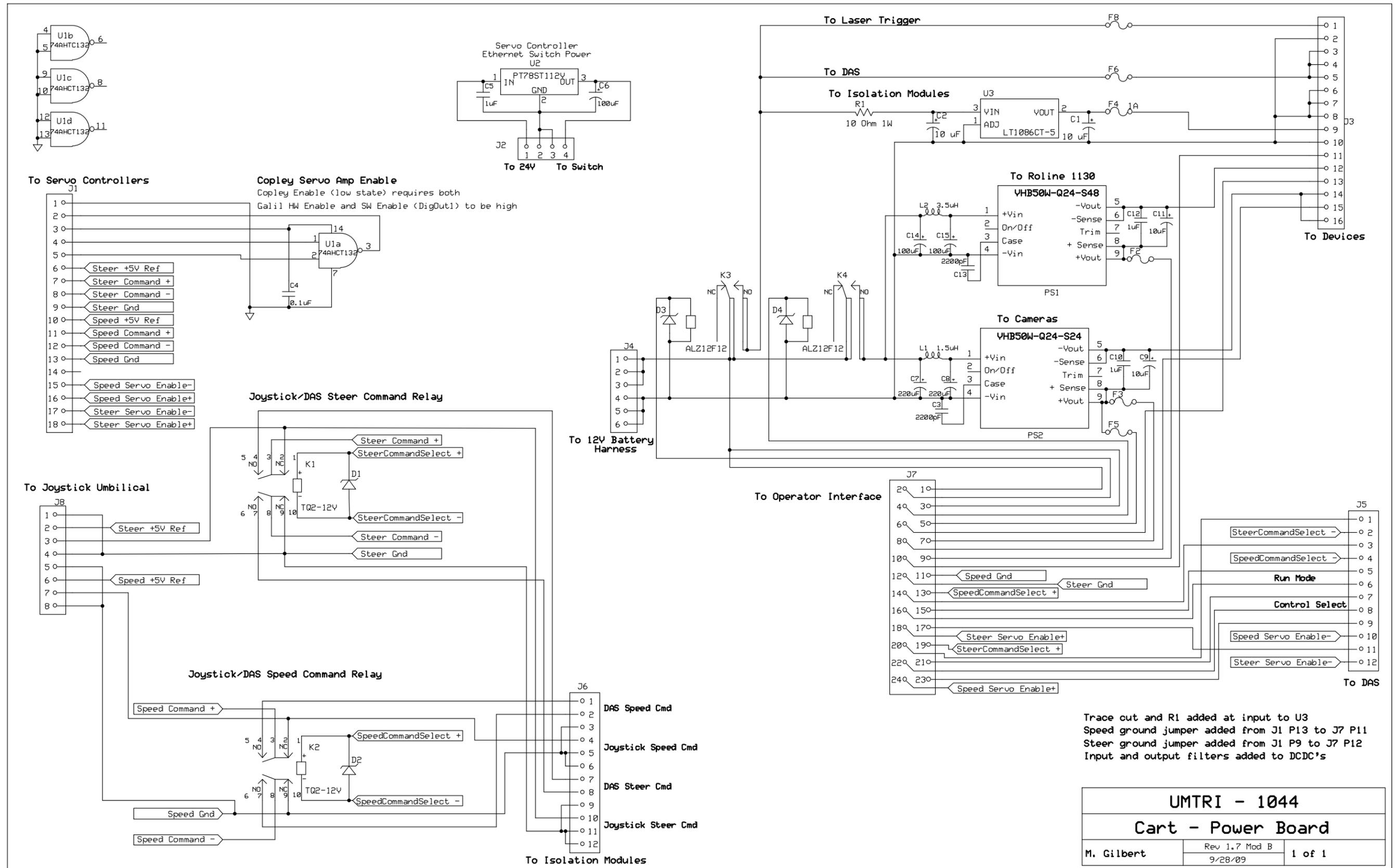
Figure F.8. Cart – Power board

Figure F.9. Cart – Power relay board
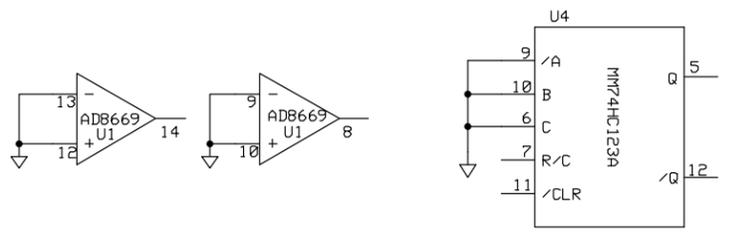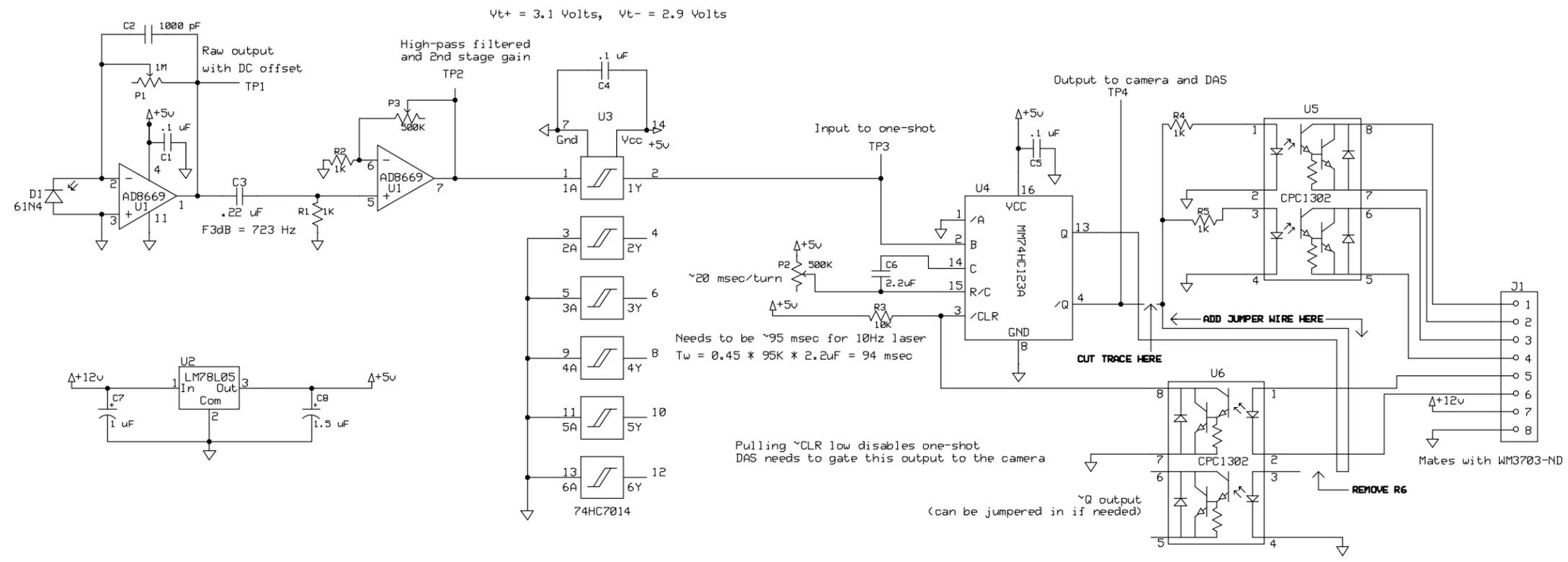
J1
Charger
+ 1
− 2

32CTQ030
D6
Servo +12V

D5
32CTQ030

J5
1
2
Molex to Run/Abort Switch
24V Mode

J2
DAS Batteries
+ 1
− 2

J6
1
2
12V to Cart
+
−

J3
Fwd Servo Battery
1
2

24V Mode
K1
5
3
1
2
4
D1
G8QN-1C4-12V
Servo +12V

J7
1
2
24V to Cart
+
−

J4
Rear Servo Battery
1
2

24V Mode
K3
5
3
1
2
4
D3
G8QN-1C4-12V
Servo +12V

24V Mode
K2
5
3
1
2
4
D2
G8QN-1C4-12V

24V Mode
K4
5
3
1
2
4
D4
G8QN-1C4-12V

Cart Power Relay Board
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Figure F.10. Rotating laser timing sensor
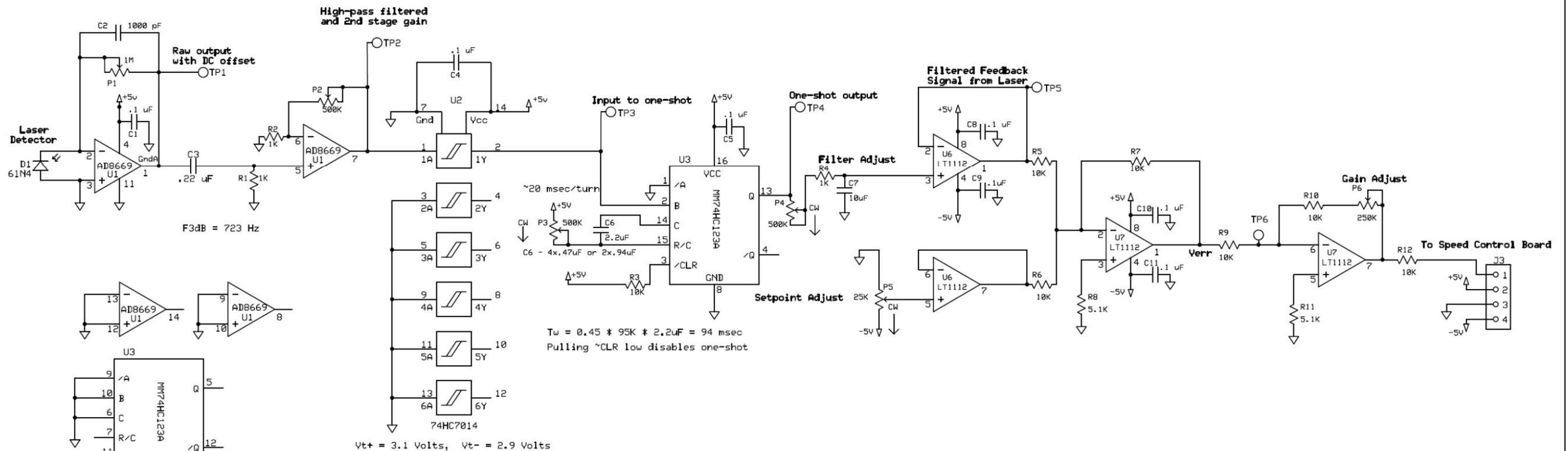
Laser Detection and Signal Conditioning (Inner Board, UMTRI-1051)

C2 1000 pF

P1 1M

Raw output with DC offset

High-pass filtered and 2nd stage gain

TP2

.1 uF C4

+5v

Laser Detector

D1 61N4

AD8669 U1

GndA

C1 .1 uF

+5v

C3 .22 uF

R1 1K

F3dB = 723 Hz

R2 1K

P2 500K

AD8669 U1

U2 7 Gnd Vcc 14

+5v

1A 1Y

Input to one-shot

TP3

+5v

.1 uF C5

One-shot output

TP4

U3 VCC 16

/A B C R/C /CLR Q GND

MM74HC123A

Filtered Feedback Signal from Laser

TP5

+5v

C8 .1 uF

U6 LT1112

Filter Adjust

R4 1K

C7 10uF

C9 .1uF

-5v

R5 10K

R7 10K

C10 .1 uF

U7 LT1112

+5v

R8 5.1K

-5v

C11 .1 uF

Verr

R9 10K

TP6

R10 10K

Gain Adjust

P6 250K

U7 LT1112

R11 5.1K

-5v

R12 10K

To Speed Control Board

J3

+5v

-5v

AD8669 U1

AD8669 U1

U3

/A B C R/C /CLR Q /Q

MM74HC123A

2A 2Y
3A 3Y
4A 4Y
5A 5Y
6A 6Y

74HC7014

~20 msec/turn

CW P3 500K

C6 2.2uF

C6 - 4x.47uF or 2x.94uF

+5v

R3 10K

Tw = 0.45 * 95K * 2.2uF = 94 msec
Pulling ~CLR low disables one-shot

P4

CW

Setpoint Adjust 25K

P5

CW

U6 LT1112

R6 10K

-5v

Vt+ = 3.1 Volts, Vt- = 2.9 Volts

Rotating Turret Speed Control and Power Supply (Outer Board, UMTRI-1050)

+24v

C20 10uF

C14 .1uF

J4

+24v A B C D

To Battery Pack

-12v

PT02A-8-4P

U4 LP2951ACM

+24v Vin Vout +5v
FB Sense
Vo tap SHDN
~Err Gnd

C15 1 uF

C16 3.3 uF

U11 TSR 1-24120

+24v VIN VOUT

GND

C21 10 uF

U10 LT1764A

Vin Vout
/SHDN ADJ
GND

R20 20K

R21 3.09K

C24 1uF

C22 100 uF

+9v

To Laser Detection Board

J2

1 +5v
2
3
4 -5v

R13 10K

U8 LT1112

+5v

C12 .1 uF

-5v

C13 .1 uF

R14 5.1K

R15 6.2K

Vin+

R16 4.7K

Vin-

U9 OPA547

V+ D2

Vo

E/S D3 R19 3 Ohm

Ilim

R17 200K

V- C23 .01uF

+9v

J1

A B C D

SW1

To Laser Power

To DC Turret Motor

PT02A-8-4S

U5 LT1964-5

GND /SHDN BYP
Vin Vout

C17 1 uF

C18 .01 uF

C19 10 uF

-12v

-5v

U8 LT1112

R18 20K

TP7

100 mA current limit R17 = ((5K*4.75)/0.1) - 31.6K = 200K

SW1 added to replace inline switch in cable to laser.
Switching regulator U11 added to drop voltage after change to 24V main supply.

UMTRI –
Rotating Laser Timing Control

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Figure F.11. Rotating laser timing control

Figure F.12. Cart – DAS interface board; 1 of 2

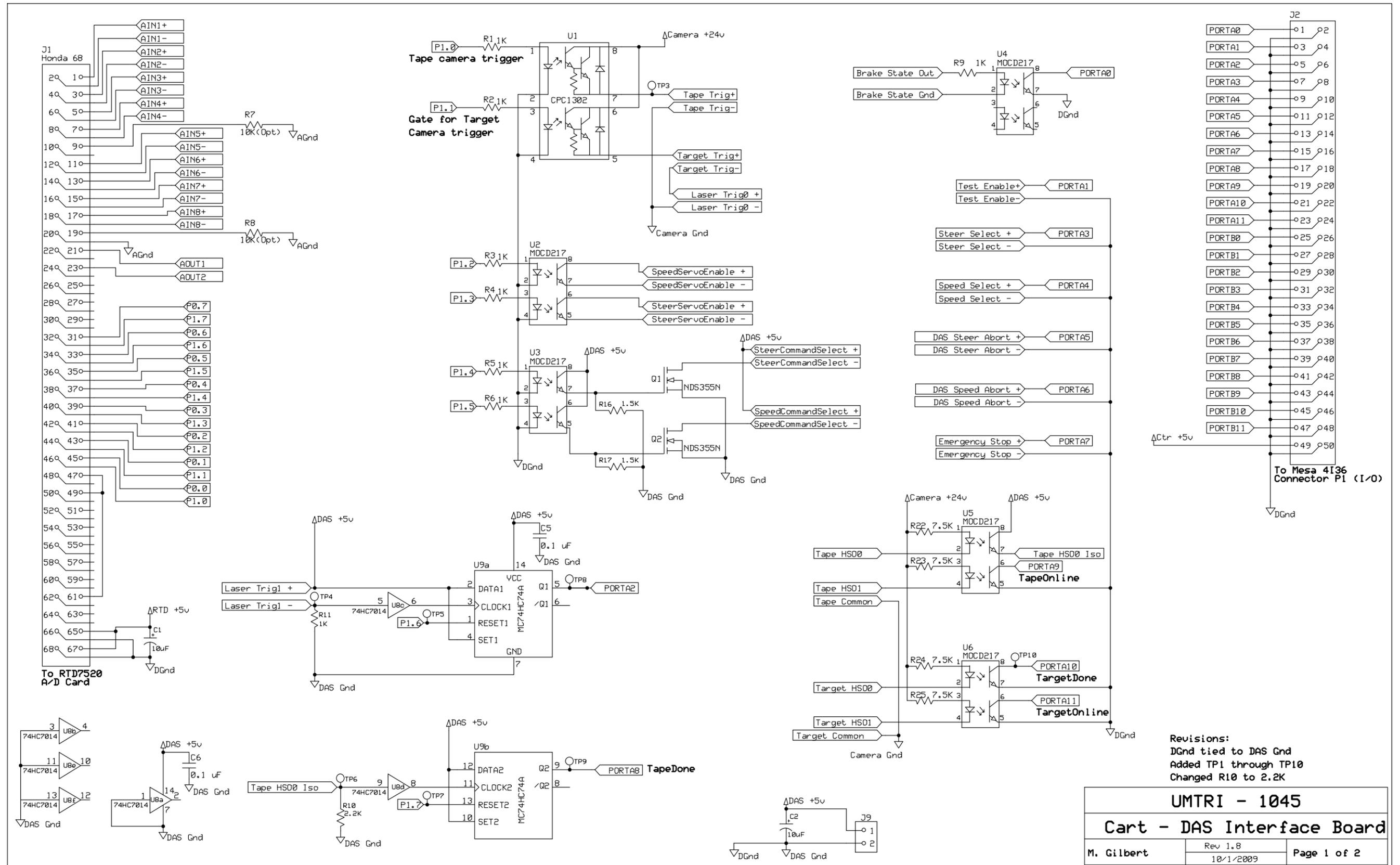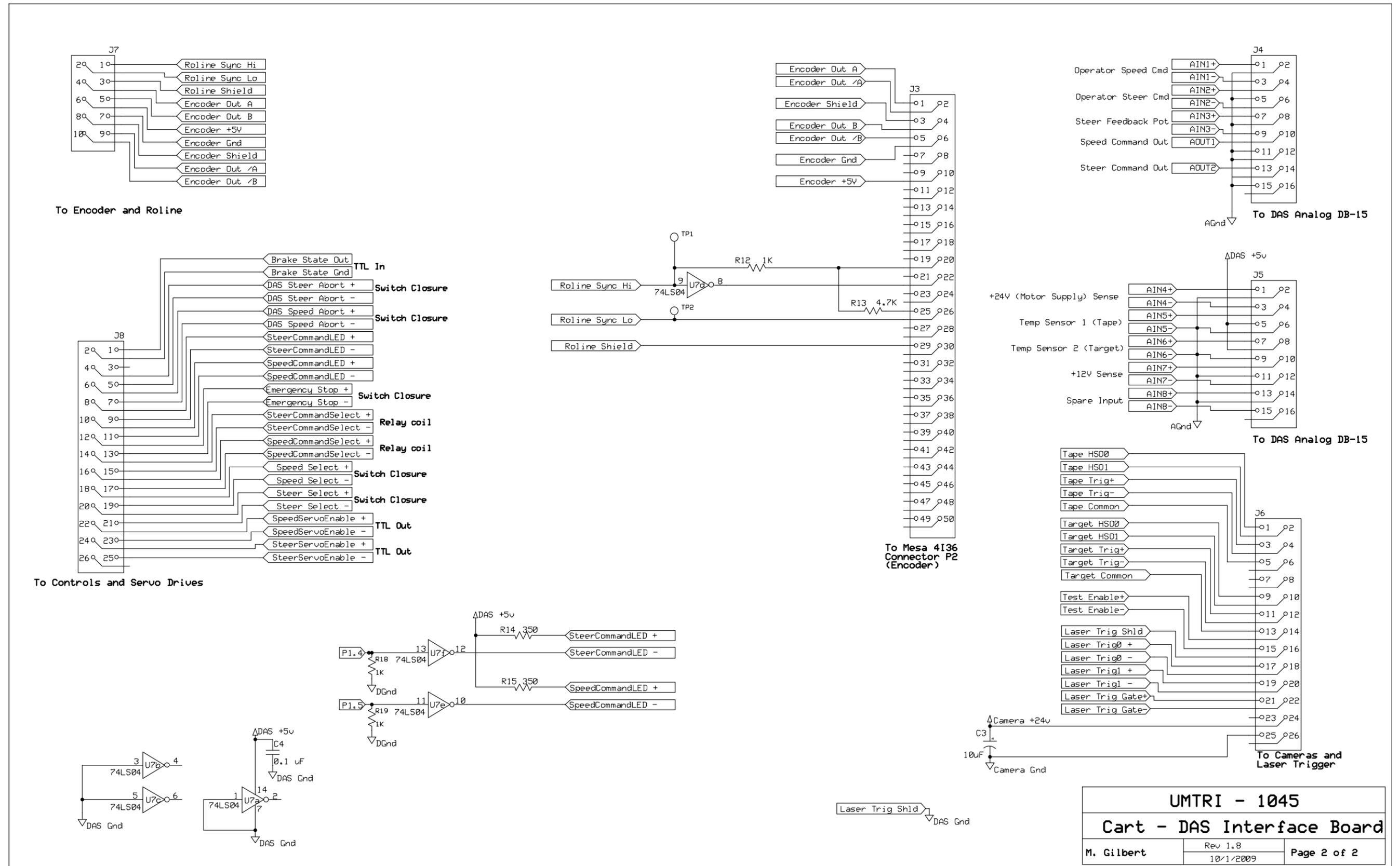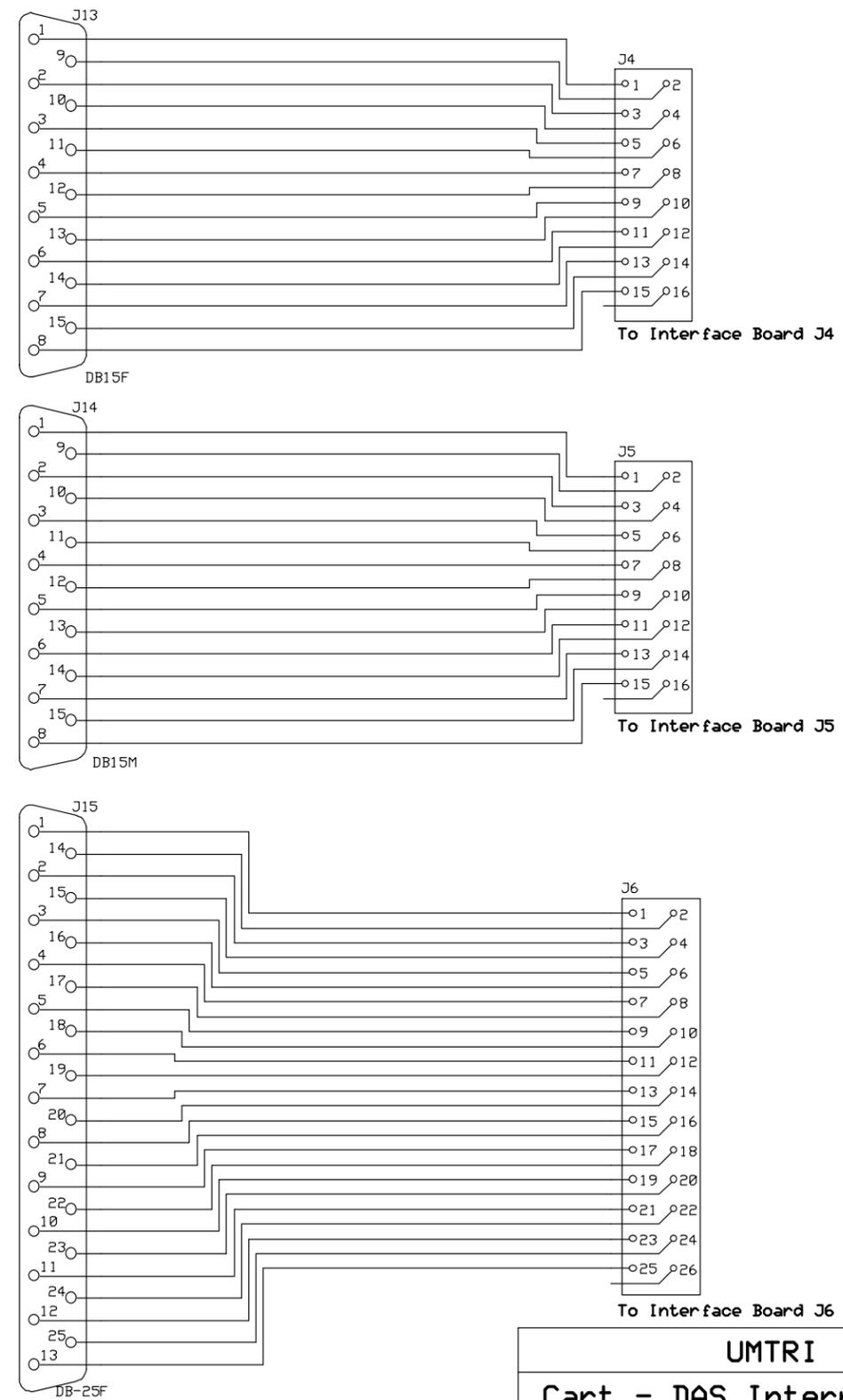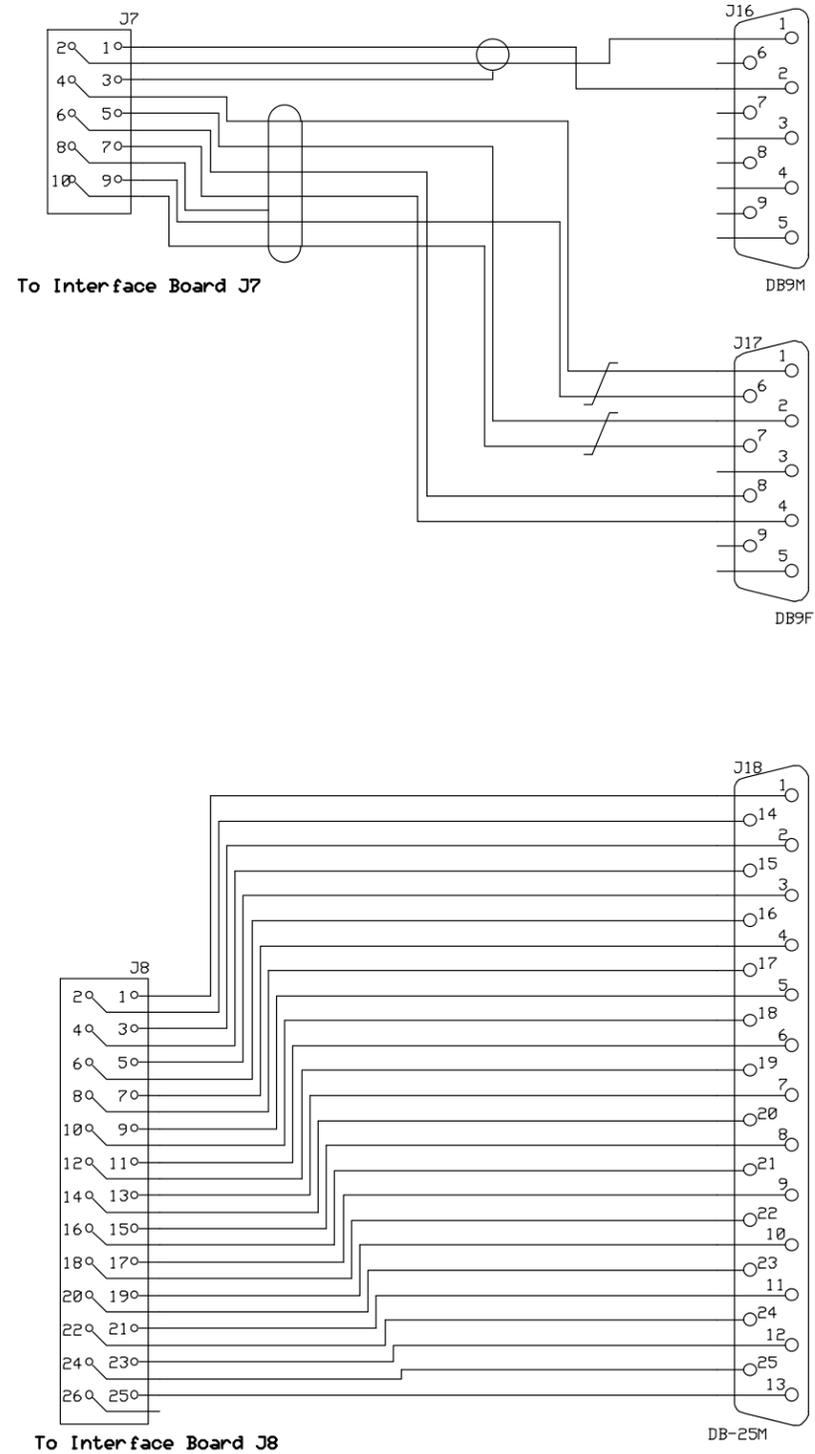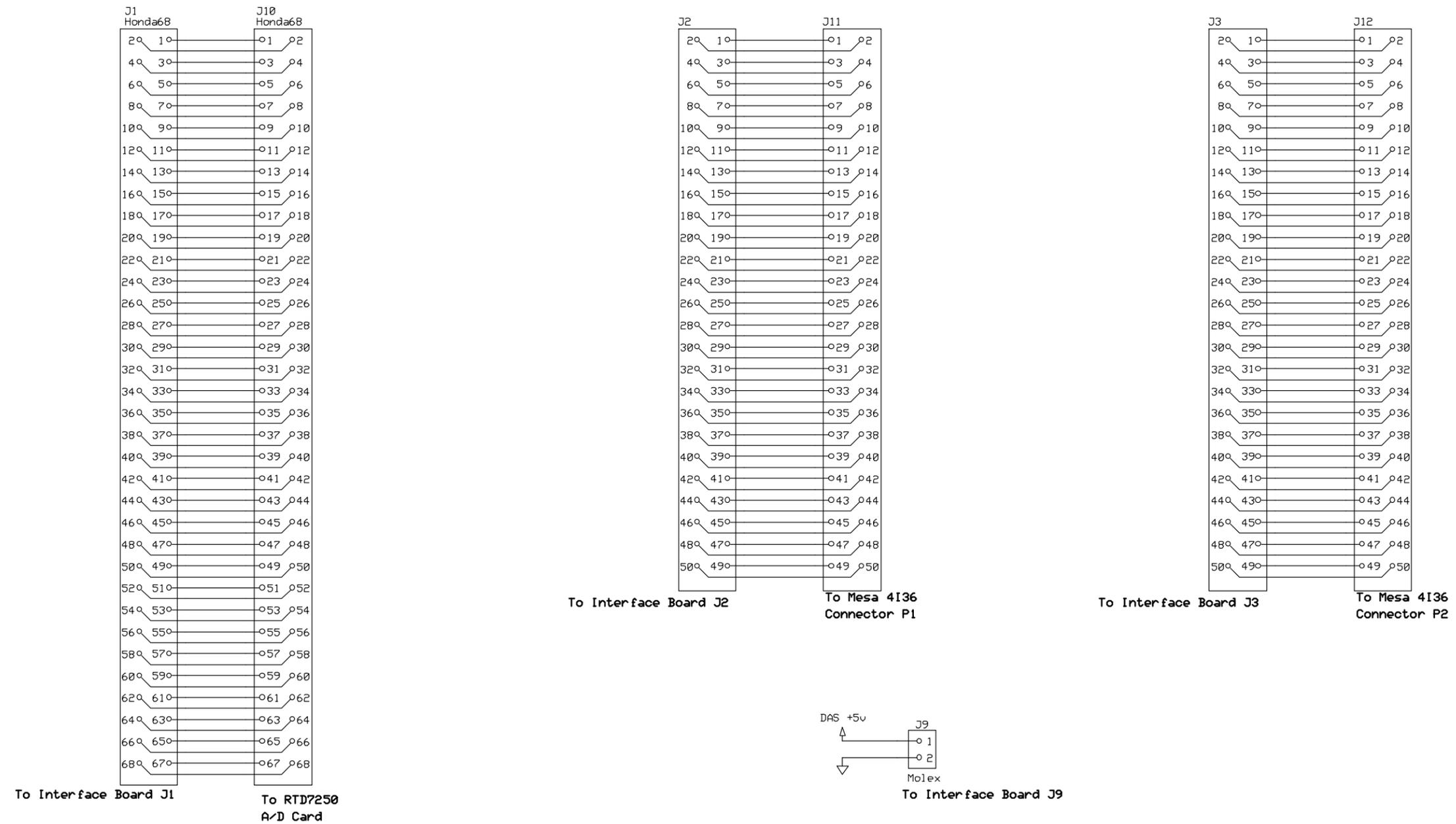Figure F.13. Cart – DAS interface board; 2 of 2

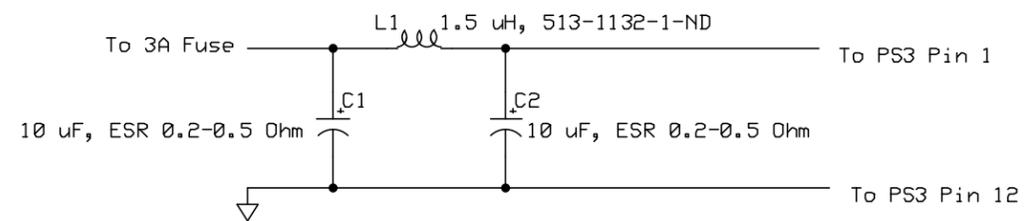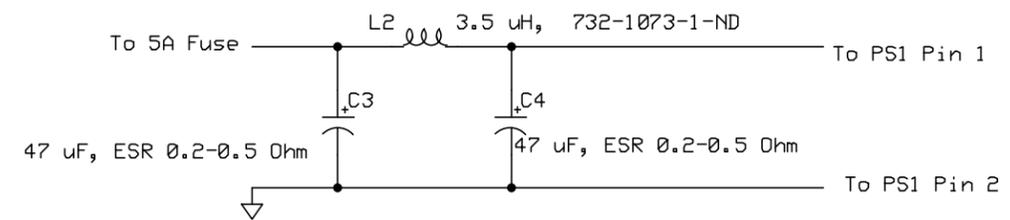**Figure F.14. Cart – DAS internal wiring; 1 of 2**

Figure F.15. Cart – DAS internal wiring; 2 of 2

UMTRI	
Cart – DAS Internal Wiring	
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To 5A Fuse ——— L2 ⌇⌇⌇ 3.5 uH, 732-1073-1-ND ——— To PS1 Pin 1

C3
47 uF, ESR 0.2-0.5 Ohm   C4 47 uF, ESR 0.2-0.5 Ohm ——— To PS1 Pin 2

To 3A Fuse ——— L1 ⌇⌇⌇ 1.5 uH, 513-1132-1-ND ——— To PS3 Pin 1

C1
10 uF, ESR 0.2-0.5 Ohm   C2 10 uF, ESR 0.2-0.5 Ohm ——— To PS3 Pin 12

UMTRI

Cart DAS Power Board Input Filters

M. Gilbert | Rev 1.0
| 1/11/2010

Figure F.16. Cart – DAS Power input filters
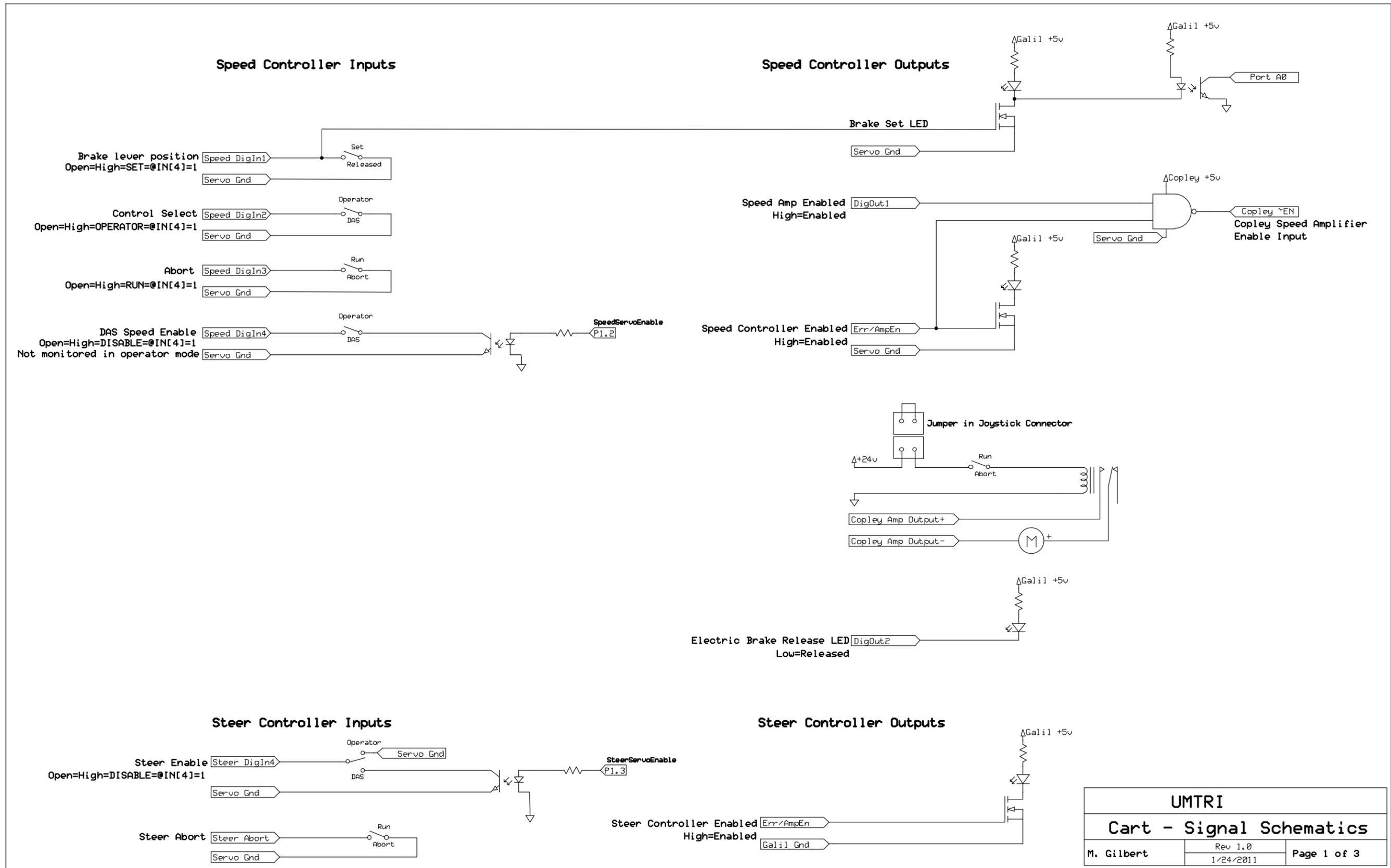
Figure F.17. Cart – Signal schematics; 1 of 3

Figure F.18. Cart – Signal schematics; 2 of 3
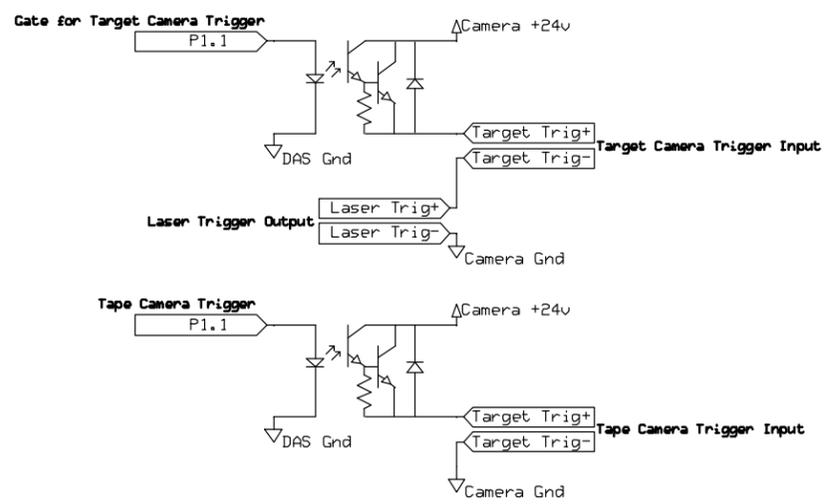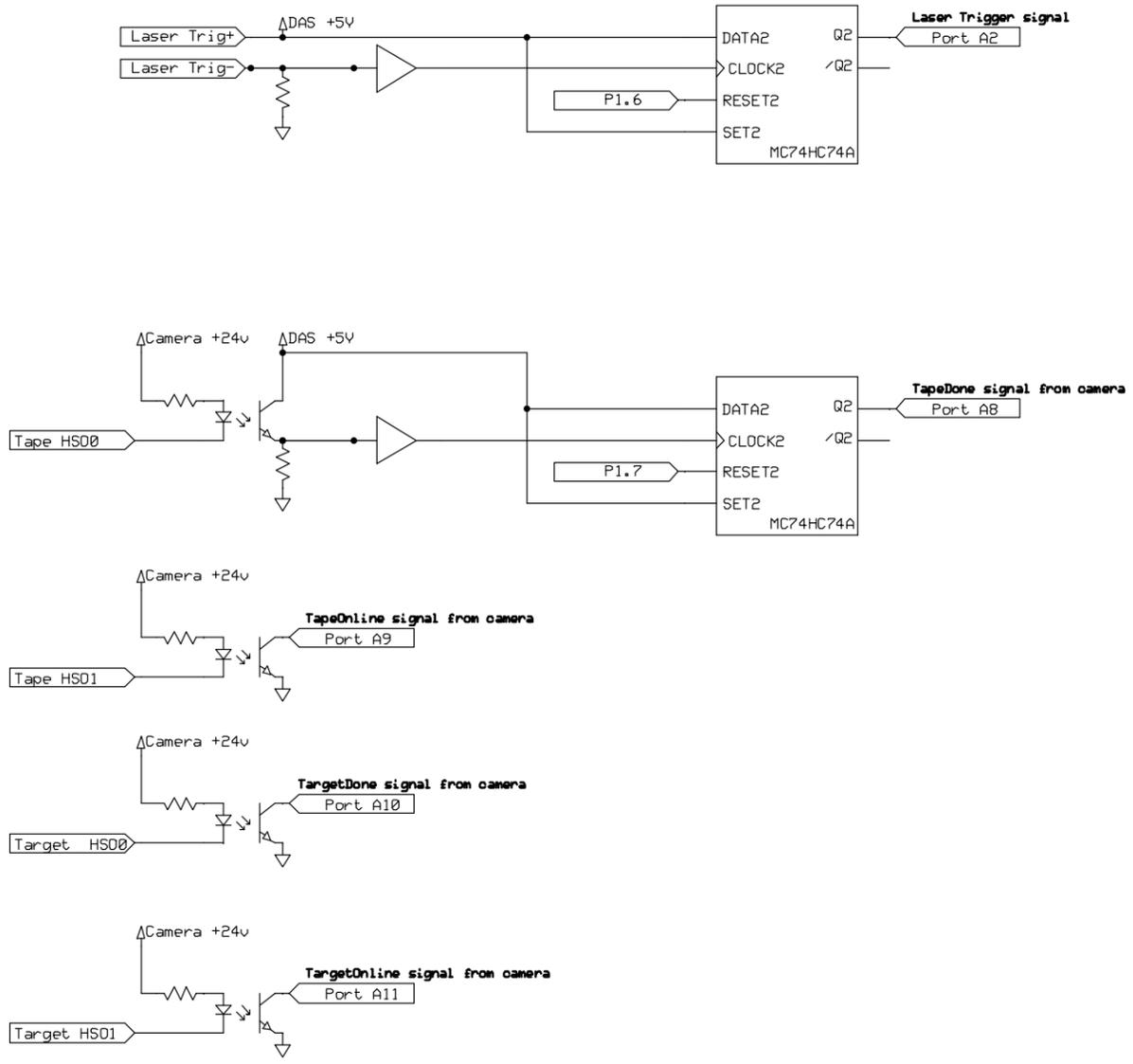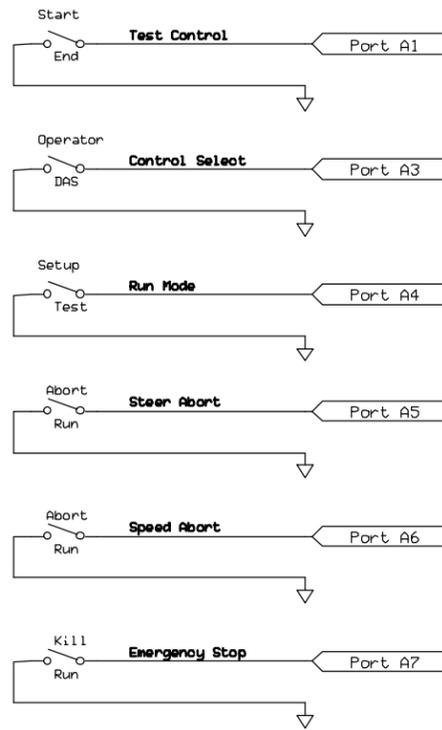
Figure F.19. Cart – signal Schematics; 3 of 3

APPENDIX G.
QUICK REFERENCE GUIDES

QUICK REFERENCE GUIDE
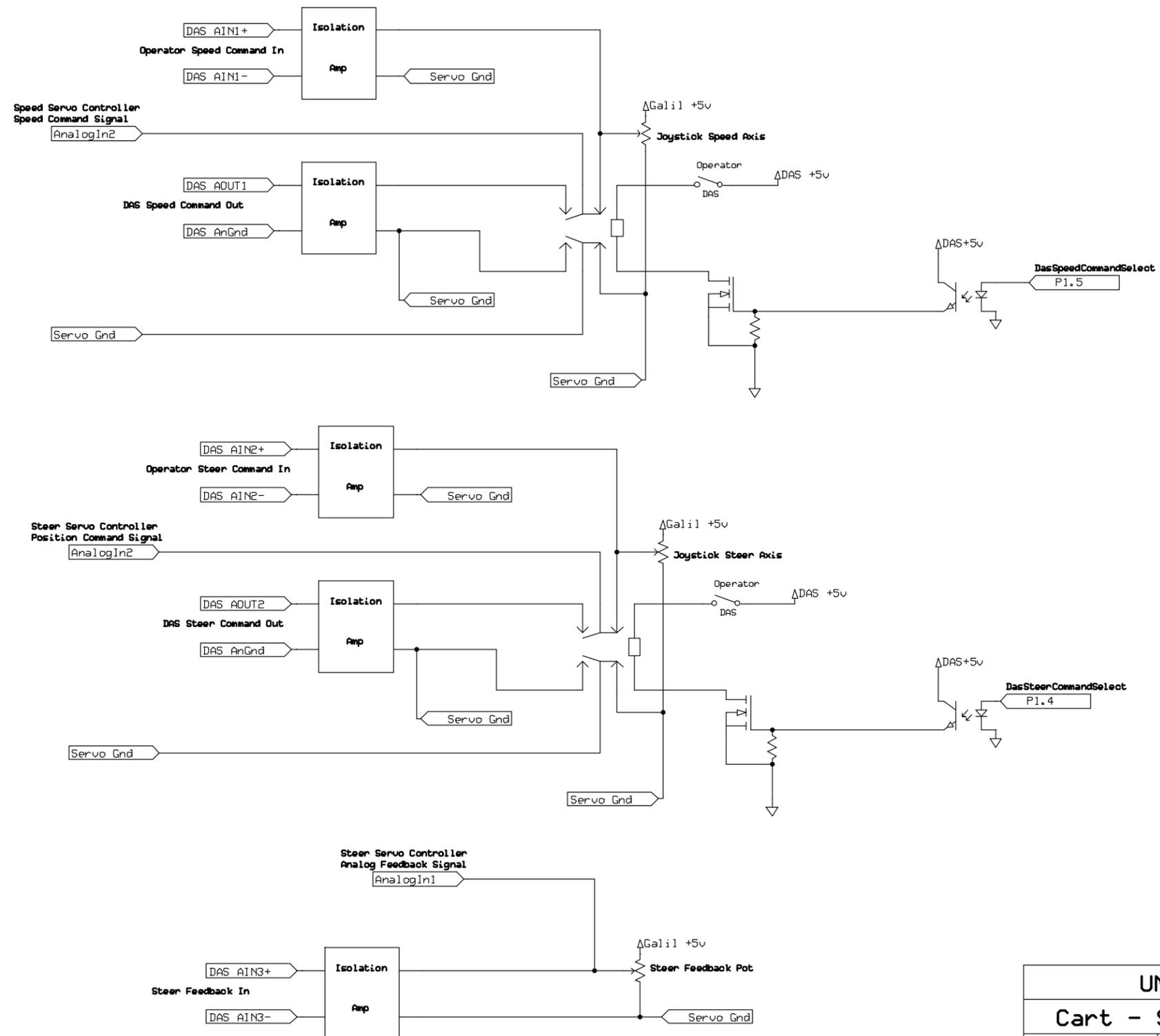### THE BENCHMARK PROFILER

Manual Driving
- Manual brake lever down (applied)
- Plug in joystick
- Select *Operator* control
- *24-Volt Master* on
- Drive using the joystick

Boot DAS and instruments
- Plug in monitor and keyboard
- *12-Volt Main Power* on
- Wait for Windows desktop
- *RoLine Power* on
- Wait for Local-area-connection message two times
- Start *Cart.exe* and *Camera Power* on
- No program other than *Cart* should be running

Conduct a test
- DAS and instruments booted
- *24-Volt Master* on
- Manual brake lever down (applied)
- Select *Operator* control: align profiler over the guidance tape
- Select *DAS* control/*Setup* mode: move profiler to starting position
- Select *DAS* control/*Test* mode
- Select *Test* menu/*Edit Parameters*: confirm/edit parameters
- Select *Test* menu/*New*: confirm/edit parameters (*RunID* incremented automatically)
- Select *Test* menu/*Start*
- *Test Control* switch to *Start*

QUICK REFERENCE GUIDE — THE SPINNING LASER
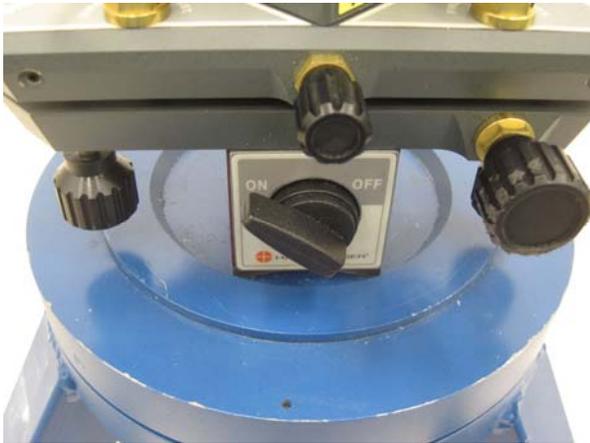
1. **Position of the laser on the tripod**
   The corners of the magnetic base firmly against the edge of the dished surface and the magnet switch on.

2. **Position of the shroud on the laser.**
   Laser controls to the rear.
   Sighting scope to the left; four thumbs screws firmly tightened.

3. **Position the assembly & power up**
   Position using the alignment plate.
   Rotate the mounting dish to aim. Lock the mounting plate.
   Connect cables & turn on switches.

4. **Level the laser in roll.**
   Use the roll adjustment and the roll bubble level to level the laser in roll.
   Repeat after step 5.
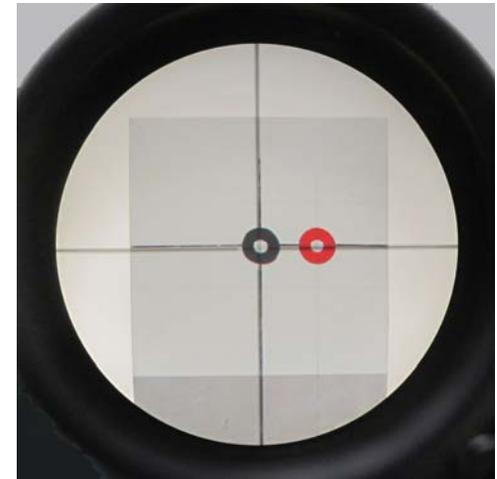
5. Align the laser in pitch and yaw.
   Use the pitch and roll adjustments and the sighting scope to align the laser in pitch and yaw.
   Repeat step 4.

APPENDIX H.
DATA PROCESSING TABLES

Table H.1. <u>LandMarks</u>**: Location of guidance tape landmarks, and residual error of linear fit of encoder vs. sectionFt**

Channel	Variable type	Description
RunId (key)	smallint	run number
pass (key)	tinyint	pass number
Encoder (key)	int	encoder value at the LandMark
SectionFt	float	position of LandMark in the section, ft
residual	real	residual error to linear fit of encoder vs. SectionFt, tics

Table H.2. <u>LandMarkFits</u>**: Linear fit coefficients for: encoder = tic0 +TicPerFt * SectionFt**

Channel	Variable type	Description
RunId (key)	smallint	run number
pass (key)	tinyint	pass number
tic0	float	constant coefficient, tics
TicPerFt	float(53)	gain coefficient, tics/ft

Table H.3. <u>Markers</u>**: Lists the encoder count and position in section of the section markers**

Channel	Variable type	Description
RunId (key)	smallint	run number
pass (key)	tinyint	pass number
MarkerType (key)	tinyint	0, startMarker; 1, endMarker
Encoder	int	encoder value at marker edge
SectionFt	real	position of marker edge in section, ft

Table H.4. <u>ProblemCodes</u>**: List of the types of data problems**

Channel	Variable type	Description
ProblemCode (key)	smallint	ID number
Problem	char(50)	Text describing problem
FatalCode	tinyint	1: fatal; 2: fatal > threshold; 3: fatal < threshold
AlertLevel	real	threshold to alter as problem, may be max or min
FatalLevel	real	threshold for fatal problem, may be max or min

Table H.5. <u>ProblemsByPass</u>**: Data problems found**

Channel	Variable type	Description
RunId	smallint	run number
pass	tinyint	pass number
ProblemCode	smallint	problem codes
ProblemValue	real	data value tested against AlertLevel

Table H.6. <u>Profiles</u>**: The final profiles; sample spacing of 5.08 mm; lateral and longitudinal bridging**

Channel	Variable type	Description
RunId (key)	smallint	run number
Pass (key)	tinyint	pass number
sectionMeter	float	position of sample in section, meter
RdElevation	real	relative elevation of the road surface, lateral and

longitudinal bridging, mm

Table H.7. RolineProfile: Subcomponents of the profile measurement; at the RoLine sample frequency

Channel	Variable type	Description
RunId (key)	smallint	run number
Pass (key)	tinyint	pass number
RolineSample (key)	int	the Roline sample number
Time	float	calculated time of this sample, csec (but finer resolution)
encoder	int	calculated (interpolated) encoder count of this sample
EdgePt	tinyint	point number of first point in 110-pt bridging field
dropOuts	tinyint	number of dropouts in the measurement field
BridgedValue	real	result of lateral bridging calculation, mm
TargetZ	real	calculated (interpolated) NearZ value, mm
LaserToRoad	real	distance from laser down to bridged "road surface," mm
SectionFt	float	position of sample in section, ft
RolineRdElevation	real	road elevation relative to first survey point of the section, lateral bridging only, mm

Table H.8. SectionFt: List the SectionFt for start and end of each segment of a section

Channel	Variable type	Description
TestSeries	int	test series number (e.g. 201009 for Sept 2010)
Site	tinyint	site number
Section	tinyint	section number
Segment	tinyint	segment number
SegmentLength	real	segment length, ft
startSecFt	real	position of segment start line in section, ft
endSecFt	real	position of segment end line in section, ft

Table H.9. Survey: Data from survey

Channel	Variable type	Description
TestSeries	int	test series number (e.g. 201009 for Sept 2010)
Site	tinyint	site number
Section	tinyint	section number of site
SectionFt	real	position in section, ft
Height	real	relative survey elevation at sectionFt, meters

Table H.10. TapePlus: Data from tape with synchronized time and additional parameters

Channel	Variable type	Description
RunId (key)	smallint	run number
Pass	tinyint	pass number
TapeSample	int	tape sample number
TapeX	real	tape value at center of tape-camera image, mm
TapeY	real	Y position of tape at center of tape-camera image, mm
TapeScore	real	tape score, percent
TapeError	smallint	tape camera error flag
Time	int	time of first occurrence of this sample in data, csec
DiffTapeY	real	TapeY(t)-0.5*(tapeY(t-1)+tapeY(t+1)
SumScore	real	TapeScore(t-1)+ TapeScore(t)+ TapeScore(t+1)
TapeYCor	real	0.5*(tapeY(t-1)+tapeY(t+1) if DiffTapeY > 4 sigma; Otherwise TapeY(t)

APPENDIX I.
ADJUSTING ROLL AND PITCH OFFSETS
IN THE TARGET CAMERA PROGRAM

I.1. Introduction

The orientation of the benchmark profiler relative to the reference plane is determined by the TargetCamera. The camera observes the track of the spinning laser as it passes across the profiler's three laser targets.[19] The program contained in the TargetCamera analyses the positions of the laser track on these targets and determines the roll, pitch and vertical position of the profiler relative to the plane of the laser beam.

The TargetCamera as delivered, has three spreadsheet programs in memory:
* *Laser.UMTRI.v0.1.job*,
* *Laser.Current.job*, and
* *Laser.ZeroAdj.job*.

As delivered, *Laser.UMTRI.v0.1.jo*b and *Laser.Current.job* are identical programs. The TargetCamera is set to run *Laser.Current.job* and go online on boot. These programs include two offset parameters for zero-calibration of roll and pitch angles, respectively. *Laser.ZeroAdj.job* is a specially altered version of *Laser.UMTRI.v0.1* intended for iterative determination of the proper values of the roll and pitch offset parameters. Once the proper values are determined, they can then be inserted into *Laser.Current.job*.

As the profiler was delivered, the zero-offset parameters in *Laser.UMTRI.v0.1.job* and in *Laser.Current.job* were properly adjusted. However, it is advisable to check the zero calibration of roll and pitch measurement prior to each test program. The procedure is described in section 5.2. If the results are found to be unsatisfactory, the first priority should be to determine why. If it is then determined that adjustment of the offset values is appropriate, that can be accomplished as follows.

I.2. Determine the Proper Values of the Roll and Pitch Zero-calibration Parameters

The procedure described below should be undertaken indoors, in still air, and under moderate to low lighting conditions.

1. Position the benchmark profiler on a level surface. Setup and run the spinning laser at a position 10 m behind the profiler as described for level reference measurement in section 5.2.

2. Turn on the 12-volt power, and turn on the power to the cameras. (The 24-volt power may be turned off.)

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[19] The two targets closest to the TargetCamera (rearward on the cart) are set to the right and left on the same plane. These are the *near* targets. The target farther from the camera (forward on the profiler) is observable by the camera between the two near targets; it is called the *far* target. See figure 1.5.

3. When the DAS has booted, run the Cognex *In-Sight Explorer* program using the shortcut icon on the DAS desktop. A screen similar to that shown in figure B.1 of appendix B will appear. (Do not run the *Cart* control program.)

4. Connect to the TargetCamera and take it offline. In the In-Sight Network window on the left (figure B.1), double click on the TargetCamera icon. (If the camera icons are not visible, be sure the camera power is on, wait two or three minutes for the cameras to boot and click the Refresh button.) When the TargetCamera has connected, the screen will appear similar to that shown in figure I.1. (The numerous #ERR indications are not a problem; they are due to the fact that the camera is not communicating with the DAS.) The online/offline indicator at the lower right will be bright green and will read "Online." Click on the online/offline icon at the upper right and confirm that you want the camera offline. The indicator will turn gray and read "Offline."
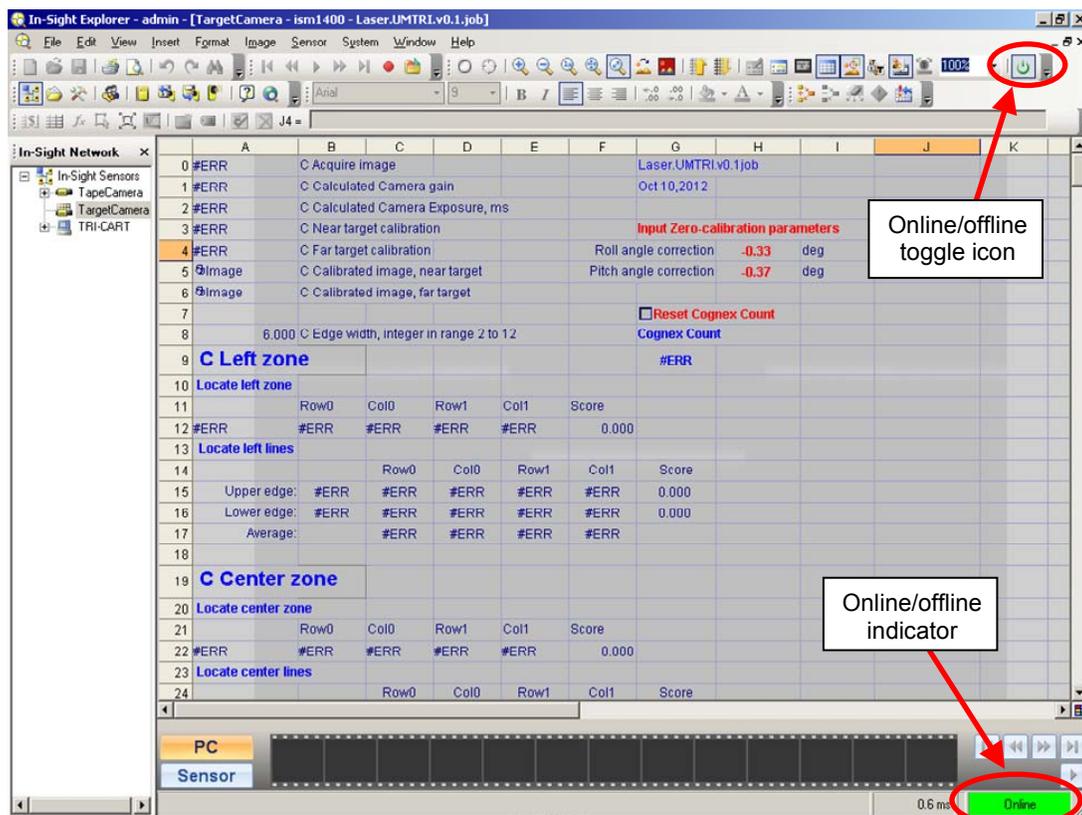

Figure I.1. *In-Sight Explorer* **screen with TargetCamera connected (Spreadsheet view)**

5. Open the *Laser.ZeroAdj.job* program. Under the *File* menu, select *Open Job* (or press Ctrl+O). The dialog box that appears will show a list of the programs in the camera memory. ("Look in: TargetCamera" will be indicated.) Select and open the *Laser.ZeroAdj.job*.

    The spreadsheet window shown in figure I.2. should then appear. (The error indicators that are evident are due to the fact that the camera has not yet generated an image.) *Laser.ZeroAdj.job* is an altered version of *Laser.UMTRI.v0.1.job* with the following modifications:

    •   Triggering the camera to acquire an image is under manual control rather than by external signal from the DAS (one of several parameters embedded in cell A1).
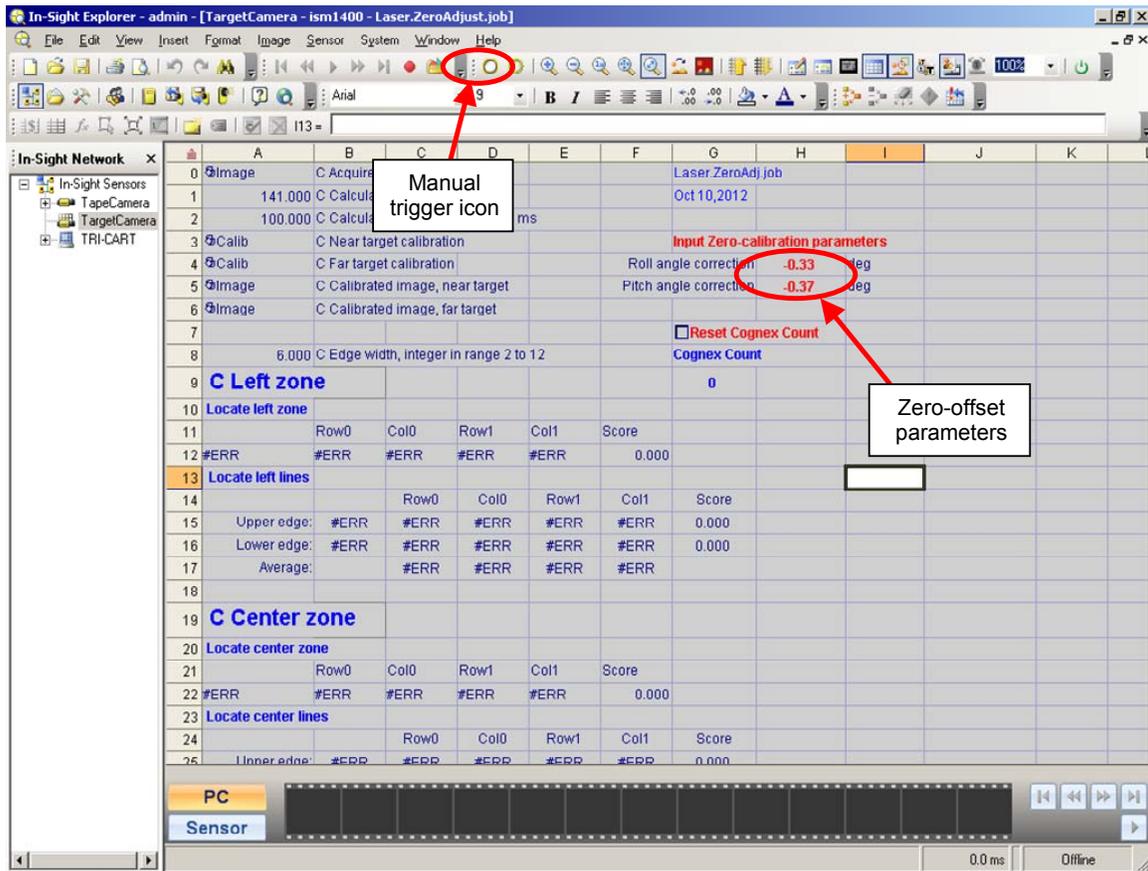
Figure I.2. *In-Sight Explorer* screen with *Laser.ZeroAdj.job* loaded (Spreadsheet view)

- Camera exposure time (cell A3) has been set to 100 ms. rather than being calculated on the basis of data received from the DAS.[20]

- Distance from the laser (cell E68) has been set to 10 m rather than being set to a value received from the DAS.

6. Determine the proper zero offset values. As shown in figure I.2, the zero-calibration offset values for roll and pitch are in cells H4 and H5, respectively. This spreadsheet is protected with entries by the user allowed only in these two cells.[21] The values in these cells may be adjusted iteratively to determine their proper value.

The manual trigger icon near the center of the control bar is also pointed out in figure I.2. Although not visible in the figure, the results of the analysis of a camera image appear in cells D55 through D59. In particular, the corrected near-plane roll angle and the corrected pitch angle appear in cells D55 and D56, respectively.

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[20] In normal use, exposure time of this camera is always less than 2 ms. and is triggered automatically just prior to the laser beam sweeping across the target screens. To insure a high probablity that a manually triggered exposure (which is randomly timed relative to the laser rotation) will capture the laser image, the exposure is set for nearly the time of a full, 360-deg rotation of the laser beam.

[21] This spreadsheet, as is the case with all the speadsheets provided in the TargetCamera and TapeCamera, is protected but without password. That is, these sheets may be unprotected under the file menu without entering a password.

6.1 Record the current zero offset values. The zero offset values for roll and pitch appear in cells H4 and H5, respectively.

6.2 Scroll down to observe the cells containing the corrected roll and pitch angles; cells D55 and D56.

6.3 Trigger an exposure. Click on the trigger icon near the center of the tool bar above the spread sheet. When the first image is acquired, all error indicators will be replaced by calculated results.

6.4 Record the resulting measures of roll angle (cell D55) and pitch angle (cell D56).

6.5 Repeat 6.3 and 6.4 several times. These measures should be repeatable within 0.01 or 0.02 deg.

6.6 Adjust the zero offset values as indicated by the observed results. If the average values of the corrected angles are not within ± 0.1 deg, adjust the roll-angle and pitch-angle offset values (cells H4 and H5) appropriately.

6.7 Repeat 6.1 through 6.6 until the proper zero-offset values are determine, and record the final values.

I.3. Insert the New Parameter Values into *Laser.Current.job*

1. Select "Open job" from the File menu, and open *Laser.Current.job* from the TargetCamera memory using the dialog box that appears (shown in figure I.2). This spreadsheet is also protected with user entries allowed only in cells G1 and G2, which contain ID comments, and in H4 and H5, which contain the zero-offset values.

2. Update the zero-offset values according to the results of step 6 of section I.2.

3. Update the ID comments if desired. <u>Take note, comments must begin with an apostrophe</u>. Take time to observe the apostrophe at the beginning of the existing comments and insure that it is retained in the updated comments.

4. Insure that the <u>Cognex count is zero</u> (cellG9) and that the <u>reset Cognex Count check box is NOT checked</u> (cell G7). In as much as the program was just loaded, these conditions should already be satisfied. However, if that is not the case, simply check and then uncheck cell G7. The program must be save in this condition for it to work properly with the DAS.

5. Save the altered spreadsheet. Do not change the file name; <u>maintain the name *Laser.Current.job*</u> as this is the program name that is set to run on startup.

6. Save a backup. It is advisable to also save an additional, backup copy of the altered spreadsheet, with a new descriptive name.