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Reliable and Intuitive Teleoperation of LineScout: a Mobile Robot for Live Transmission Line Maintenance

Nicolas Pouliot, Pierre Latulippe and Serge Montambault*, Hydro-Québec research institute

Simon Tremblay, Averna

***Abstract* – Power line inspection and maintenance is a slowly but surely emerging field for robotics. This paper describes the control scheme implemented in LineScout technology, one of the first teleoperated obstacle crossing systems that has progressed to the stage of actually performing very-high-voltage power line jobs. Following a brief overview of the hardware and software architecture, key challenges associated with the objectives of achieving reliability, robustness and ease of operation are presented. The coordinated control through visual feedback of all motors needed for obstacle crossing calls for a coherent strategy, an effective graphical user interface and rules to ensure safe, predictable operation. Other features such as automatic weight balancing are introduced to lighten the workload and let the operator concentrate on inspecting power line components. Open architecture was considered for progressive improvements. The features required to succeed in making power line robots fully autonomous are also discussed.**

Index terms—Field robotics, telerobotics, wheeled robot, power line inspection robot.

I. INTRODUCTION

Over the last five years, numerous initiatives have been undertaken to develop robots for transmission line maintenance, as presented extensively in a recent review paper [1]. Although most efforts have so far resulted in lab prototypes, the need for such technologies is expressed clearly in the roadmaps of a growing number of electric utilities [2][3].

Since 1998, Hydro-Québec has been actively developing transmission line maintenance robots. From a simple remotely operated motorized trolley [4], the project has evolved into the teleoperated robot LineScout, which has been in operation since 2006 on some of the Hydro-Québec TransÉnergie grid's 32,000 km of transmission lines.

Early in the LineScout project, the objective was to develop a robot capable of operating in an extreme environment (live lines of up to 735 kV) and under harsh field conditions. The technology had to be safe and reliable since it operates on one of every country's most strategic assets, the power grid. Open architecture is a design goal so state-of-the-art technologies and new application modules may be introduced as they become available or required. Finally, LineScout must be teleoperated, with the capacity to ultimately evolve into an autonomous vehicle. These specifications are all linked to the control strategy.

Some aspects of the technology have already been presented, i.e., technical specifications for the early design [5], the geometrical design [6], the complete validation process [7] and logistical details relevant to deploying such technology under real field conditions [8]. However, this paper covers for the first time LineScout's control strategy. After introducing the control hardware and software, the authors explain the key components that were assembled to produce reliable, intuitive technology open to gradual improvements. Although some authors presented control algorithms for the lab prototype of their transmission line robot [9]-[12], the approach described herein was found effective towards the successful introduction of the technology in transmission line maintenance operations. Future applications are briefly discussed.

II. OVERVIEW OF THE TECHNOLOGY

This section presents an overall description of LineScout's mechanical design, obstacle-crossing strategy, on-board electronics and ground control unit in order to provide a basis for later discussing the control strategy.

A. Mechanical systems and crossing strategies

LineScout's moving platform was devised as a two-wheel vehicle to optimize energy efficiency as it travels along obstacle-free sections of power lines. Two brushless DC motors, labelled DIS1 and DIS2 in Figure 1, are thus dedicated to LineScout travel. Mounted next to the wheels, a pair of safety rollers, actuated by DC motors ROL1 and ROL2, secures the robot to the line as it stops next to the obstacle to cross.

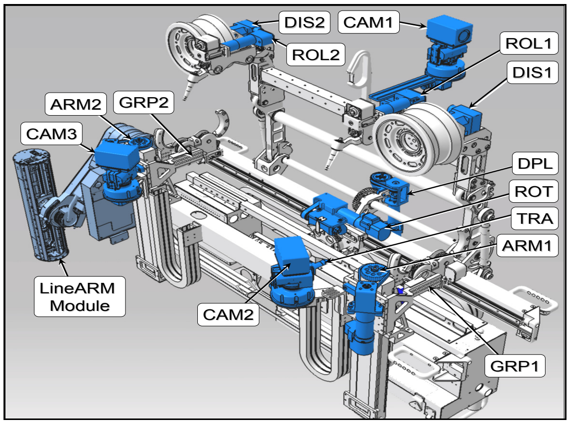

Fig. 1. LineScout motors, cameras and module description.

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* Corresponding author : montambault.serge@ireq.ca

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The robot structure that allows the clearing of obstacles is build around three independent frames that slide and pivot relative to one another: the wheels are attached to the wheel frame, the arm frame supports two gripper arms that grasp the conductor to either side of the obstacle while crossing and the centre frame links the first two frames. The latter also supports much of the robot's weight, including the battery and electronics cabinet, plus the two DC motors, ROT and TRA, used to deploy the frames. TRA is equipped with an electromagnetic brake, as are ARM1 and ARM2, which motorize gripper arms GRP1 and GRP2 controlling the opening of the grippers. Lastly, DC motor DPL deploys a mechanism that brings down the wheel frame's upper portion. The use of these systems is clarified by Figure 2, which presents the crossing of a suspension clamp.

Figure 1 also shows the location of the three programmable pan-and-tilt camera (PPTC) units that provide visual feedback to the operator. CAM1 is mounted on the wheel frame, while CAM2 and CAM3 are on the arm frame. The LineARM module, also labelled in Figure 1, is not required to cross obstacles. However, when LineScout is equipped with this module, it allows a fourth PPTC and various tool modules to be used.

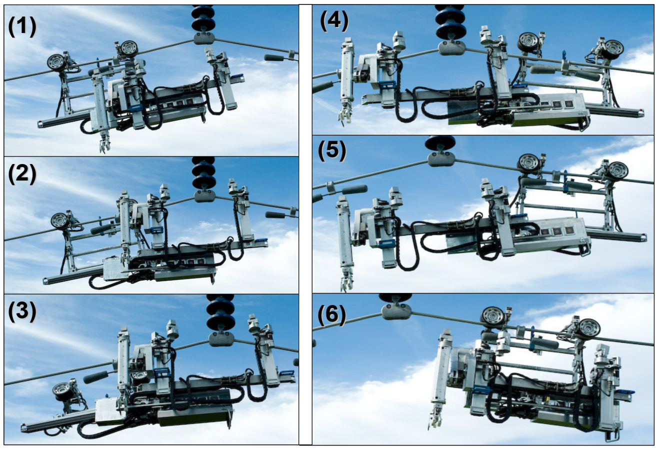


Fig. 2. Obstacle-clearing strategy: 1) LineScout deploys the arm frame under the obstacle. 2) Gripper arms rise and grippers clamp onto the conductor. 3) Rollers are released from the conductor; wheels are lifted slightly and then lowered by the deploying mechanism. 4) Translation and rotation occur in the opposite direction. Deploying mechanism raises the wheels. 5) Wheels are back on the conductor and rollers have secured their hold. Grippers open and gripper arms are lowered. 6) Arm frame returns to its initial position and rollers open so LineScout can continue its route.

B. *On-board electronics*

The LineScout communication scheme revolves around two major systems: the on-board electronics (OBE) installed inside the robot, and the ground control unit (GCU) used by the operator. OBE subsystems are now described using Figure 3.

The bidirectional data antenna (1) is linked to the RF card (2), which communicates with the GCU. The converted radio signal is carried over an RS-232 link to the main controller (3), which interfaces the RS-485 bus (4). Another role of the main controller is to coordinate speed control of brushless motors DIS1 and DIS2 through their dedicated motor amplifiers (5). Since both motors are mechanically coupled to the conductor through the wheels, special care had to be taken in designing the PID control loop.

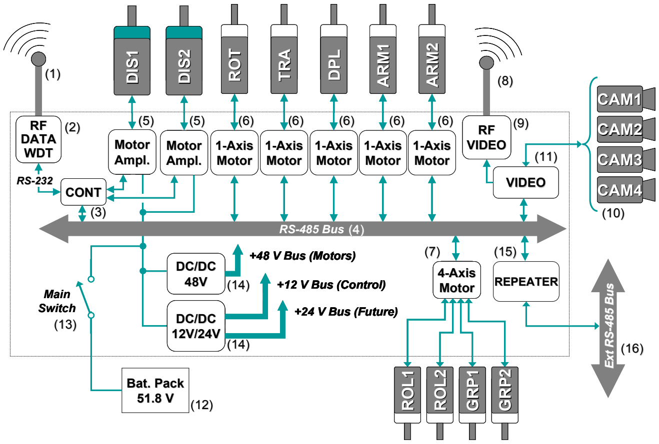


Fig. 3. Schematic of the on-board electronics (OBE).

In fact two distinct control loops were devised, one for each motor. Whenever the speed set point is equal to zero, the two PID control loops are completely independent. This allows different torques to be generated, as required for example when only one wheel is in contact with the conductor. When the speed set point is not equal to zero, the PID control loops must not be independent. Due to small differences in their contact radii or while rolling on obstacles, the rotational speed must tolerate an error in the integral term; otherwise, stresses would build up in the structure. To avoid this, the two integral error values are averaged and fed into each control loop.

The motor amplifiers (5) also have a built-in feature that electrically impedes DIS1/DIS2 rotation if communication is lost in order to slow LineScout down if it is on a steep slope.

Five DC motors (ROT, TRA, DPL, ARM1 and ARM2) have dedicated cards (6) with a 6-A motor amplifier for closed-loop speed control. Four others (ROL1, ROL2, GRP1 and GRP2) are under open-loop control using a single 4-axis card (7) with four 6-A motor amplifiers. Position feedback for each motor, however, is provided analogically by a potentiometer.

A unidirectional antenna (8) and its transmitter (9) are used to transmit the video signal from one of the four PPTCs (10) or from two combined by the video multiplexer (11). This card controls each of the cameras over an RS-232 link. This link also communicates with the internal PCB of the PPTC to control the pan-and-tilt motors, either with speed or position set points.

The energy source is a 51.8 V Li-ion polymer battery pack (12) turned on and off at the main switch (13). This unregulated voltage level directly supplies the brushless motor amplifiers. Three buses carry different voltages produced by DC/DC converters (14): 48 V for DC motors, 12 V for control features and 24 V for sensor applications. Finally, the main RS-485 bus signal is amplified (15) and routed outside (16) the electronics cabinet to communicate with peripheral tools, such as the LineARM.

C. Ground control unit

The ground control unit (GCU) consists of ruggedized components housed in a custom-designed, transportable, folding container, shown in Figure 4. It provides a complete solution for field operation of LineScout and serves as a development platform as well.

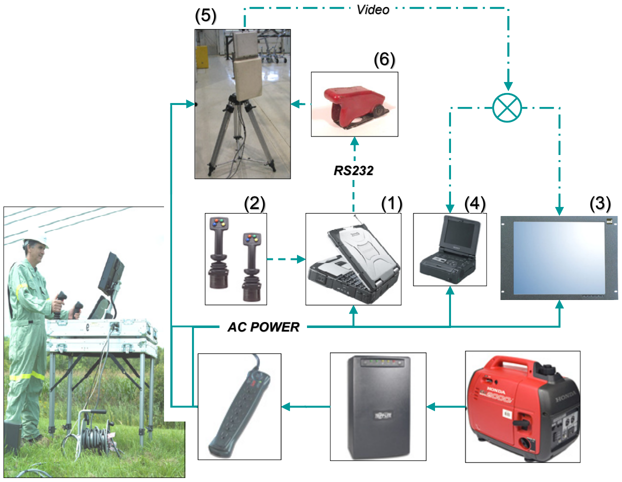


Fig.4. Schematic of the ground control unit (GCU).

At the centre of the system is a mil-spec touch screen mobile computer (1) that runs NI LabVIEW on Windows XP. Two industrial 3-axis joysticks (2) are connected as input devices. The right joystick is for controlling LineScout's axis of movement while the left joystick is for controlling its PPTC units. Video signals are routed from LineScout to the GCU's video monitor (3) via an RF video receiver (5) and can be archived by a MiniDV recorder (4). Data signals are routed from LineScout to the GCU's mobile computer via an RF data transceiver (6). An emergency stop switch (7) cuts off data communications.

At this point, it is important to describe the custom-designed communication protocol, inspired by the MODBUS industrial standard [13]. OBE subsystems are configured in parallel, each with its own data address. As stipulated by the MODBUS standard, registers are used to exchange data and the GCU can communicate with any OBE subsystem by referring to its address. Unlike the MODBUS standard, however, in order to minimize the number of RF transmissions between the GCU and OBE, data elements are grouped in packets so they can be sent or received together. Packets are structured by creating write lists (L_W) and read lists (L_R), and require that a series of registers first be associated with specific physical OBE boards. The main controller defines the lists, collects the relevant data and sends it throughout the OBE in response to a GCU request. Using this procedure, it becomes possible to read from or write to several registers on different boards at once. Furthermore, unlike with the MODBUS standard, it is even possible to read and write register lists in a single transmit/receive cycle. Concretely, using lists makes it possible to send multiple (position or speed) set points to motors and receive multiple encoder positions together.

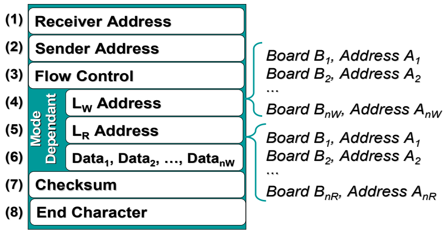


Fig. 5. Communication packet format.

As shown in Figure 5, a data packet is composed of n 8-bit characters. It includes receiver (1) and sender (2) addresses to specify the OBE board to which the packet is destined. There is also a flow control field (3) that specifies the type of request, L_W (4) and L_R (5) addresses, data D_W (6), the number of values n_W that must be copied to the registers specified by L_W, a checksum (7) and a final end character (8). The OBE returns n_R, the number of values contained in the registers specified by L_R. Data packets are typically exchanged every 80 ms.

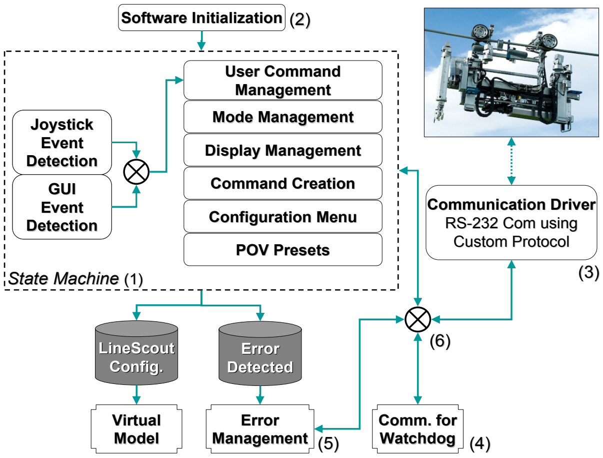


Fig. 6. Architecture of the LineScout control software.

The main architecture of the GCU software (Figure 6) is based on a state machine (1) that initializes the program (2), and handles all graphical user interface (GUI) and joystick events. It sequences data communication between the GCU and OBE by sending and receiving data using the communication driver (3). Also, three separate threads are executed in parallel. The watchdog communication thread (4) is a temporized loop that confirms communication. The error detection loop (5) manages any LineScout encoder malfunctions without blocking control signals. The virtual model thread (6) is presented in following section. All communication packets are queued to avoid collisions.

III. KEY CHALLENGES AND SOLUTIONS

Factors beyond those for a general mobile demonstration robot, e.g., ease of error-free operation and operator training, robustness and reliability requirements, and the need to minimize workload so that the operator can focus on the actual line inspection, were paramount in control system design. These challenges and the associated solutions are now discussed.

A. *Intuitive control of numerous actuators*

Several actuators must be controlled as LineScout moves along the conductor, crosses obstacles and performs inspections tasks. Remote operation of such a robot from a few kilometres away implies that effective feedback must be provided and also that the control strategy results in simple and intuitive control of the robot.

1) *Mode operation strategy*

Considering the number of actuators to control and the amount of data received from LineScout (encoders, stops, status, etc.) the concept of mode operation strategy (MOS) was introduced to minimize operator workload and the risk of error.

MOS is a way to restrict operator access to only the specific group of actuators that is relevant to the action being performed. Each axis of the right joystick is mapped to a motor, or a pair of motors, so that controlling LineScout feels natural to the operator, ensuring more user-friendly control. Assuming that the X-axis is horizontal (left-right), the Y-axis is vertical (up-down) and the Z-axis is a twist of the joystick (positive or negative), Figure 7 gives a snapshot of each mode, and the motors assigned to each axis and to the four buttons.

MOS	REF	X	Y	Z	Z+Trig.	Buttons
TRAVEL	W	p·⎡DIS1 ⎣DIS2				ROL1 ROL2
FRAMES		p·TRA		p· ROT		
GRIPPERS		p·{ARM1 ARM2				GRP1 GRP2
FLIP/CROSS	G	-p·TRA	-p·⎡ARM1 ⎣ARM2	-p· ROT	DPL	ROL1 ROL2
HOMING		TRA	⎡ARM1- ⎣ARM2-	ROT	DPL+	ROL1,2- GRP1,2+
TOOLS						

Fig. 7. MOS summary layout.

When the robot rolls along the line, TRAVEL mode is active and both wheel motors, DIS1 and DIS2, are assigned the same speed settings, as indicated by the square bracket in Figure 7. The purpose of the integer p will be defined in the next section.

Three modes are dedicated to various phases of obstacle crossing: FRAMES, GRIPPERS and FLIP/CROSS. The sequencing of the mode, indicated by the arrows in Figure 7, guides the operator by suggesting a specific flow through the modes and is consistent with the obstacle-crossing strategy. Furthermore, it provides a clear path that limits possible errors.

In HOMING mode, the motors slowly move to their home position and encoder values are reset. Lastly, there is the TOOLS mode for splice measurement and LineArm use, details of which are not described here.

Each mode can be configured independently by the settings of the following elements:

- Activation of the PPTC unit presets (see Section C-1)
- Configuration of L_R and L_W (see Figure. 5), i.e., the set points and information relevant to the mode
- Sensitivity of each motor defined by a threshold and maximum velocity. Generally, if we define k as a signed 16-bit integer from the k-axis of the joystick, so that $k_{MAX} = 2^{15}$, the velocity set point associated with motor MOT is equal to $\pm(k / k_{MAX}) \cdot \dot{MOT}_{MAX}$.

As shown in Figure 7 for GRIPPERS mode, it is also possible to control two actuators using a pair of joystick axes, as indicated by the curly brackets next to motors ARM1 and ARM2. In this case, the Y-axis dictates the top speed set points at which both gripper arms can move and the X-axis modulates linearly the differential speed of each arm. In other words, both arms move at the same speed unless the X-axis is biased towards one of the grippers, slowing the other gripper arm down to a halt. This very intuitive feature was implemented by sending the following set points:

$$\dot{ARM}1 = \dot{ARM}_{MAX}\left(\frac{y}{k_{MAX}} \times \mathrm{MAX}\left(1,\ 1-\frac{p\cdot x}{k_{MAX}}\right)\right) \qquad (1)$$

$$\dot{ARM}2 = \dot{ARM}_{MAX}\left(\frac{y}{k_{MAX}} \times \mathrm{MAX}\left(1,\ 1+\frac{p\cdot x}{k_{MAX}}\right)\right) \qquad (2)$$

Where $k_{MAX} = x_{MAX} = y_{MAX} = 2^{15}$ and $\dot{ARM}_{MAX}$ is the maximum allowable speed for the arm.

2) *Point of view and frame of reference*

Since LineScout can be teleoperated from a distance of few kilometres, the operator must rely on video feedback. The operator can select any of the cameras, which are mounted to either side of the conductor. The rendered point of view (POV) will thus depends on the choice of cameras and will be roughly perpendicular to the conductor. Figure 8 shows examples of the POVs resulting from selecting different cameras. The CAM2 and CAM3 split view images to the left give “front” POVs. The CAM1 images to the right provide “rear” POVs.

Depending on whether the front or rear POV is selected, parameter p, used in Figure 7, is either set equal to 1 or -1, changing the sign of the speed set points transmitted. As a result, pushing the joystick laterally in a certain direction will always have the intuitive effect of a movement towards that direction, as visualized with the active POV, thus reducing mental rotations as suggested by [14] or [15].

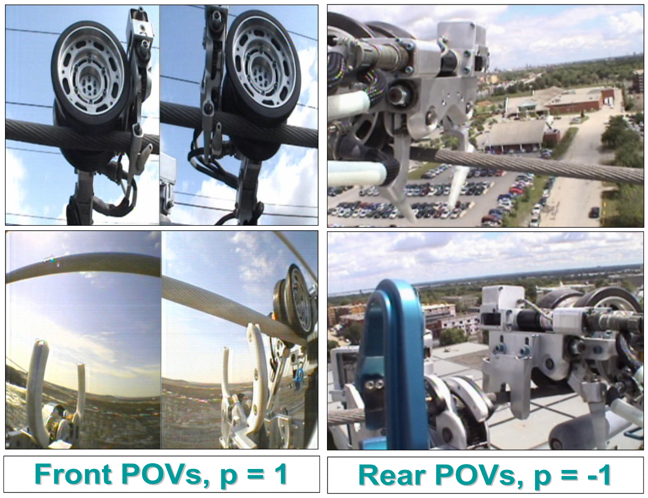


Fig. 8. LineScout operator points of view (POVs).

The active frame of reference is similarly specified in a way to ensure intuitive LineScout control. It determines which components are fixed with respect to the conductor. The two possibilities are "grippers", when the grippers clamp onto the conductor during the FLIP/CROSS mode, and "wheels", when the wheels sit on the conductor (other modes). There is also a transitory "redundant grasp" phase when both rollers and grippers cling to the conductor, and during which movement is impossible. Again, the effect of changing from one frame of reference to the other will reverse the set points of some motors, as indicated by the minus signs for FLIP/CROSS mode (Figure 7). The joystick thus has the intuitive effect for the operator inputting a direction.

3) *LabVIEW graphical user interface*

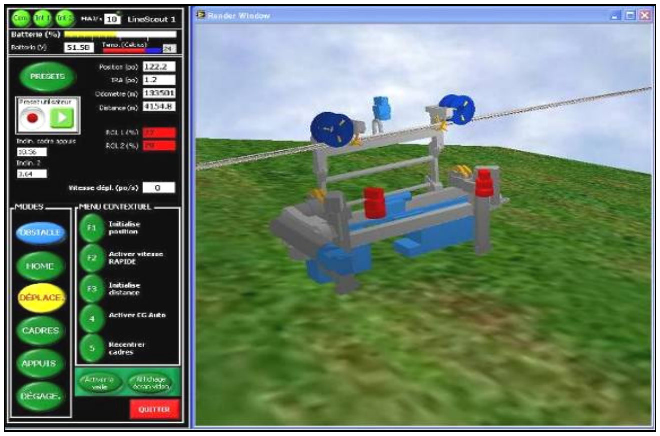
As shown in Figure 9, the main graphical user interface (GUI) is divided into 2 zones: a control window (left) and a virtual model of LineScout updated in real time (right).

The control window is the main user interface and is designed with the touch screen philosophy in mind, i.e., buttons are oversized, well-spaced and easy-to-reach. Contrast is also important for added clarity since the GCU is to be used outdoors.

The most common user inputs are handled by the joysticks. They are used to select modes, activate actuators, select camera views, etc. The main user interface complements the joysticks and allows the operator to input advanced commands. It also displays LineScout actuator positions, stops, inclinometers, battery level, communication status, etc.

The layout of controls and indicators is mode-specific, displaying only the relevant buttons and information. A context-sensitive menu is updated to give access to specific functions related to the current mode.

Although the operator's main visual feedback is given by the cameras, the virtual model window plays the important role of providing at a glance an alternate overall view of LineScout configuration. LabVIEW's Open GL package allows models from 3D CAD to be loaded, displayed and animated. Each mobile model is loaded and assembled based on the current encoder readings, as well as inclinometer roll and slope readings. Furthermore, active cameras are highlighted in red for quick reference.



Batterie (V) 51.50
Position (po) 122.2
TRA (po) 1.2
Odometre (m) 133501
Distance (m) 4154.8
Vitesse dépl. (po/s) 0

Fig. 9. LineScout graphical user interface (GUI).

B. *Robustness and safe operation*

The use of a teleoperated robot on assets as strategic as transmission lines has a major impact on the design. The robot itself must have a high level of reliability and must include systems that prevent it from causing damage in the event of a failure. Moreover, its control system must override any human error that could damage the robot or line components, threaten linemen or jeopardize public safety.

LineScout must work reliably in an environment that is very harsh for the electronics, due to several types of electrical disturbances: strong electric fields, partial discharges from the robot structure, very high voltages, high currents and associated magnetic fields. For that reason, double conductive shielding is installed over all wiring and connected to the continuously conductive mechanical structure.

The inside of the OBE must also be EMI-protected. This is why several low-density CPUs are used instead of one centralized high-density CPU. The clock may thus be set to a much lower frequency making the entire system less prone to being affected by EMI disturbances. Having no central operating system or on-board hard disks also simplifies the system and improves overall system reliability.

The watchdog thread, briefly presented in an earlier section, is also a key component for robot robustness. A dedicated circuit is built into the main controller and checks for proper communication between the GCU and OBE by acknowledging receipt of two distinct timer resets. Upon miscommunication, the watchdog immediately disables the 48 and 51.8 VDC power buses.

Since relative-position encoders are used throughout the robot, an unexpected power shutdown would cause all motor homing positions to be lost. To avoid this, the RF data card in the OBE detects any shutdown by monitoring the main switch and sends a signal to the controller so all encoder values are saved to non-volatile memory. To perform this action, a hold relay maintains the power on the robot for about 4 seconds.

To avoid human errors and situations where LineScout could be damaged accidentally, three kinds of safety interlock rules have been implemented throughout the control software. The complete list of interlocks was built over time by logging any misuse or errors by less experienced operators.

The first kind is a restriction on set points based on LineScout configuration. One typical interlock reduces, and beyond a certain position completely ignores, the speed set point when approaching a mechanical stopper.

Another important kind of interlock allows or blocks mode changes. There are specific conditions that must be met before entering or exiting a mode. One such rule blocks access to FRAMES mode whenever the safety rollers (ROL1 and ROL2) are not completely attached to the conductor.

The envelope-type interlock defines a safe 2D working space for two actuators moving concurrently. For instance, the working envelope for motor ROT is defined with respect to motor TRA. This has the effect of dynamically modifying the ROT axis limits based on the actual value of TRA, so that $\dot{\mathrm{ROT}}_{\mathrm{MAX}}$ is ramped down to zero close to this virtual limit.

C. *Assisted operation*

Additional solutions have been implemented to provide the operator with means to focus on the most important task, safe operation of the mobile platform as it travels on the live line and crosses obstacles.

1) *Camera orientation presets*

Obstacles can be crossed using several combinations of movements and configurations. However, most obstacles can (and should) be crossed using the same sequence. It may be helpful to prompt the operator to follow that sequence as it results in a more consistent way of controlling the robot. The use of camera presets that provide optimal visual feedback during the crossing sequence is one effective way to encourage all operators to use the best pattern.

In order to implement the presets, PPTC unit motors must be equipped with encoders, cameras coordinates (c_i) and target (e.g., wheel, conductor and grippers) coordinates (t_j) must be defined with respect to some rigid body, and LineScout's kinematic equation must be derived from its current configuration.

These factors being known, the objective is to select a camera and a target. A series of frame transformations is performed by going through all LineScout's rigid bodies to obtain a unitary vector specifying the direction vector that the camera must follow to display the target. This vector is converted into pan (θ_P) and tilt (θ_T) coordinates using the following equations, with Figure 10 illustrating the terms:

$$\theta_P = \mathrm{ATAN2}(\mathrm{V_Y}, \mathrm{V_X}) \tag{3}$$

$$\theta_T = 2 \cdot \mathrm{ATAN}\left(\frac{-\mathrm{V_{XY}} + \sqrt{\mathrm{V_{XY}}^2 + \mathrm{V_Z}^2 - r^2}}{\mathrm{V_Z} + r} \right) \tag{4}$$

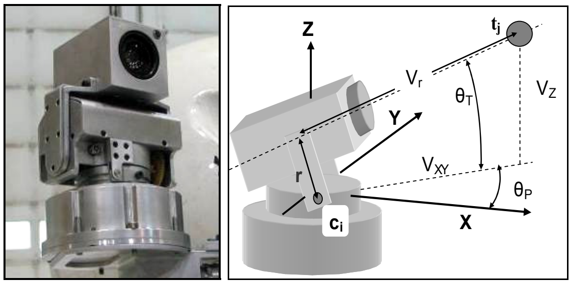


Fig. 10. PPTC unit and conventions associated with preset equations.

2) *Automatic balancing of the load on each wheel*

In order to be stable, LineScout's centre of gravity is intentionally located as far as possible beneath the conductor, at a distance L_1 = 0.55 m as shown in Figure 11. When climbing steep slopes, this significantly shifts the weight to the higher of the two wheels. As an example, since the LineScout wheelbase is 0.77 m, a slope of 25 degrees will lead to a front-to-rear weight ratio of 80%-20%. This could cause the rear wheel to start slipping.

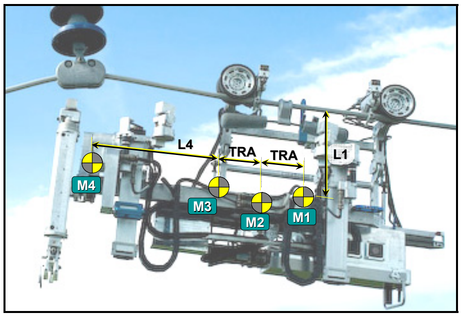


Fig. 11. Schematic for centre of gravity estimate.

To offset this, motor TRA can be used to reposition the frames. This was implemented as an automated feature, using the slope reading θ_S from an inclinometer. Referring to Figure 11, four localized weights are distinguished, associated with the wheel frame, centre frame, arm frame and LineARM module respectively. For simplicity, it is assumed that all four weights are located at a vertical distance L_1 from the conductor. Also, since the LineARM module may or may not be mounted, factor A = {0, 1} is introduced to calculate the total weight as:

$$M_T = M_1 + M_2 + M_3 + A \cdot M_4 \tag{5}$$

The horizontal position of the overall centre of gravity with respect to the centre of the wheel frame is given by:

$$x = \frac{M_1 + TRA \cdot M_2 + 2TRA \cdot M_3 + (2TRA + L_4) \cdot A \cdot M_4}{M_T} + L_1 \cdot Tan(\theta_S) \tag{6}$$

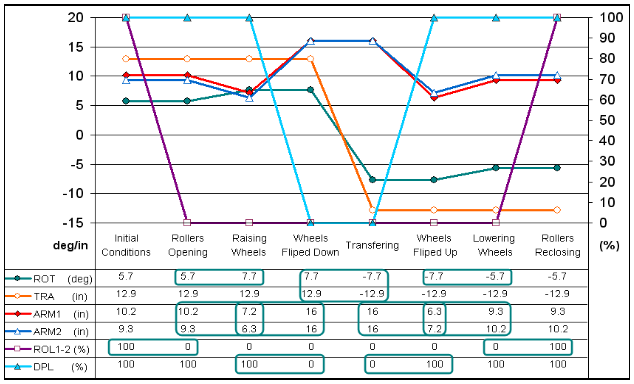
If we set equation (6) to zero, the controller can update the position of TRA with respect to the measured slope θ_S, using:

$$TRA = -\frac{M_1 + L_4 \cdot A \cdot M_4 + L_1 \cdot M_T \cdot Tan(\theta_S)}{M_2 + 2(M_3 + A \cdot M_4)} \tag{7}$$

This control is used in TRAVEL mode only, at the operator's request.

3) *Automated crossing sequences*

The next step in assisting the operator is to develop sequences for automatically crossing repetitive obstacles under operator supervision, minimizing the probability of error.



deg/in	Initial Conditions	Rollers Opening	Raising Wheels	Wheels Fliped Down	Transfering	Wheels Fliped Up	Lowering Wheels	Rollers Reclosing
ROT (deg)	5.7	5.7	7.7	7.7	-7.7	-7.7	-5.7	-5.7
TRA (in)	12.9	12.9	12.9	12.9	-12.9	-12.9	-12.9	-12.9
ARM1 (in)	10.2	10.2	7.2	16	16	6.3	9.3	9.3
ARM2 (in)	9.3	9.3	6.3	16	16	7.2	10.2	10.2
ROL1-2 (%)	100	0	0	0	0	0	0	100
DPL (%)	100	100	100	0	0	100	100	100

Fig.12. Automated crossing sequence.

This automated sequence starts at step 2 in Figure 2, when the grippers are on either side of the obstacle. The sequence is based on the theoretically symmetry between starting and final configurations (i.e., readings from ROT, TRA, ARM1 and ARM2). As shown in Figure 12, the sequence is divided into several steps and the speed at which the sequence is executed is proportional to operator input using the Y-axis of the joystick.

The sequencer uses the starting position to calculate the final configuration. Speed set points are parameterized linearly as a function of a common parameter t, and they are sent until the required position or a stop is reached. The next step is then initiated and the process repeated until the sequence ends or is halted by the operator.

D. *Open architecture considerations*

As the technology makes its way into maintenance practices, new needs will arise from end users. An open architecture approach was adopted from the outset to support probable evolution of the technology. The decision to go with teleoperation (versus a fully autonomous robot) allowed the robot to be introduced into field operation fairly early in the development process and to gain credibility within the user community. However, the possibility of evolving towards a fully autonomous vehicle was never discarded.

One of the key aspects of the software is the mode operation strategy (MOS), which was designed to be extendable. A generic template is provided for new modes so the programmer can quickly assign a control scheme, establish a data read list, define interlock conditions, define movement coordinates, and program specific functions easily.

In terms of OBE hardware, the choice of PICs in conjunction with custom-made PCBs allows for quick additions as needs arise. For that purpose, several extra I/O entries were included in the initial board design. Extending the RS-485 communication bus combined with a power bus outside the OBE provides greater flexibility to add new sensors.

The PPTC units are all mounted on interchangeable quick-connect bases. New camera presets can also be implemented using existing or new targets, simply by entering coordinates relative to one of the LineScout reference frames.

Lastly, GCU hardware was selected with the goal of supporting future enhancements: the touch screen interface allows for quick reconfiguration, and each joystick axis and button can be mapped to accommodate a wide variety of options.

IV. CONCLUSION & FUTURE WORK

The set of control features presented enabled LineScout technology to be used in a reliable, intuitive and effective way under real field operation conditions. A balance was struck between advanced functions that lighten the operator's workload and proven industrial-type control principles.

The use of LineScout on the transmission lines of Hydro-Québec and other utilities led to valuable input for improving and extending the technology. Most future work will be directed toward enhanced teleoperation, additional modules to perform more complex tasks and developing fully autonomous technology.

1) *Enhanced teleoperation*

Two upgrades to structure instrumentation are planned. The first aims at identifying and managing internal mechanical constraints during the redundant grasp phase (see Section

III-A-2). This would result in a more fluid behaviour during every sequence of movement when crossing an obstacle. The second upgrade will introduce a weight-on-wheel (WOW) sensor, inspired by the system found on aircraft landing gear. This will improve automatic obstacle-crossing capacity since symmetry need no longer be assumed in moving the wheels on the other side.

2) *Performing more complex tasks*

Future live-line maintenance jobs will rely on the use of the LineArm. Numerous areas of research and development have been identified: dexterous manipulation, introducing force-torque feedback, collision detection, introducing additional degrees of freedom, implementing new sensor technology and developing end effectors for specialized jobs.

3) *Developing fully autonomous technology*

Considering that few technologies have actually been applied on the power grid, a step-by-step approach is wise in looking towards fully autonomous technology. Obstacle detection and identification, initiated by some teams [16]-[20], will soon become an inescapable issue. The diversity of line components found on grids contributes to the complexity of the task. However, challenges such as waterproofing, improving energy autonomy, automatic line fault detection, and longer range teleoperation must be addressed concurrently to produce an autonomous robot that is really useful for power line utilities.

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