APPLYING MARTIAN ROVER TECHNOLOGY TO SOLVE TERRESTRIAL PROBLEMS: THE DEVELOPMENT OF AN AUTONOMOUS COLD-TRAILING OMNIRANGE ROBOT (ACTOR)

Amor Menezes, Rowena Luk, Paul Tsz Yeung Lam, Ziad Bhunnoo

Department of Mechanical Engineering
Department of Electrical and Computer Engineering
University of Waterloo
Waterloo, Ontario, N2L 3G1
Canada

amenezes@uwaterloo.ca, rluk@uwaterloo.ca, ptylam@uwaterloo.ca, zabhunno@uwaterloo.ca

KEYWORDS

Autonomous, cold-trailing, mobile robot, rover, forest-fire, hotspot detection, Martian technology applications.

ABSTRACT

All the forest's a stage, and all the fires and their fighters merely players; they have their exits and their entrances, and one ACTOR in its time plays many parts, its acts including hotspot detection and mapping.

With the successful completion of NASA's 2003 Mars Exploration Rovers mission and the well-documented triumph of the Pathfinder Sojourner rover in 1997, the autonomous capabilities of mobile robots to explore and map hostile environments have been proven. But although the tremendous potential for these rovers has been demonstrated, extensive research in "search-and-discover" robotics has yet to be implemented in terrestrial applications. Specifically, one direct application of the Martian rover is its usefulness in detecting and mapping hotspots in the aftermath of a forest fire, serving as a safer, faster, more efficient alternative to current human-centric methods within an inhospitable environment. It is difficult to find evidence that such an application has ever been previously attempted.

The majority of a firefighter's time is spent uncovering glowing embers among the ashes of forest fires, to prevent any resurgence of flames in the undergrowth. *Cold-trailing* for hotspots is a tedious task, often resulting in burns to the hands of the firefighters. Furthermore, helicopter infrared systems do not display a fine enough resolution over large tracts of land when there is interference from smoke or clouds, and areas of brush are challenging to investigate. An Autonomous Cold-Trailing Omnirange Robot (ACTOR) may be developed to solve this problem; indeed, it can be shown that such a task is an ideal application of Martian rover-based technologies.

A proof-of-concept robot that addresses such issues was designed and prototyped, and its details are outlined in this paper. It draws from the Martian rovers in four key aspects – 1) *mechanical construction and control*, utilizing adaptable tracked wheels that permit mobility on rough, uneven terrain; 2) *auxiliary sensors*, enabling the ACTOR to perceive its environment, and localize based on the grid information previously stored; 3) *perception* to resolve conflicting or intermittent signals from auxiliary sensors into a realistic and probable world view; 4) *path-planning* to determine the next physical step required of the rover; and 5) *wireless communication*, updating a remote control station by notifying users of the location and intensity of potential ember sites, and also permitting human intervention as required. Once a basic rover is implemented with these four subsystems, the design is improved and extended to fire-fighting applications with the addition of a *thermal imaging vision system*. Full-scale implementation of such a robot would be of immense practical value in the wake of the fires that devastate the world's forests each summer, by increasing the efficiency and accuracy of contemporary firefighting techniques.

In documenting the design process of a terrestrial application of the Martian rover, the ACTOR Project seeks to demonstrate the feasibility of the transfer of space technology to the fire-fighting industry, in addition to exemplifying the adaptation of rover ideas to education applications.

1 INTRODUCTION

The phenomenal success of NASA's *Opportunity* and *Spirit* Mars Exploration Rovers (MER) in 2003 has, like its forerunner *Sojourner* during the *Pathfinder* mission of 1997, renewed public interest in the capabilities of mobile robotics and reaffirmed the commitment to land humans on the red planet. Roving the surface of another world millions of kilometers away, these robots have captivated imaginations and stimulated new interest in the technology. As a result, the term "rover" has become almost exclusively reserved for a wheeled robot operating in a harsh, unfamiliar environment (typically one that is extra-terrestrial), serving as a scout in areas where it is unsafe or impractical for man to explore. This association has led modern earth-bound humans to neglect the uses that such an extreme-environment vehicle can have on Planet Earth.

Rover technology then, has had limited terrestrial application by virtue of its rather narrow scope. Yet there are some areas that are suitable – rescue robotics[7]; terrorist and bomb threat investigations; and various industrial, hospital and museum surveillance, inspection, and transportation tasks[8, 13] to name a few. In each case however, the robots are still in the developmental and prototype stages. It is possible to speed up the design process by directly applying the research already incorporated within the Martian rovers, if one can establish sufficient similarity in operating environment and user specifications for other robots. One of the goals of the Autonomous Cold-Trailing Omnirange Robot (ACTOR) project was to design and prototype a scale rover with MER-like functionality for a completely new application in the forest-firefighting industry, by transferring ideas from its Martian counterpart. It is difficult to find evidence of such an application having ever been previously attempted. Not only would this project demonstrate the feasibility of the transfer of space technology, but it would also serve to broaden awareness of the underlying principles of the Mars rovers within the education milieu, as part of a senior undergraduate design project.

The following sections look at the "cold-trailing" application in detail, and verify the suitability of transferring technology from the Martian rovers. Section 4 identifies precisely how this can be accomplished, by drawing from four key systems: mechanical construction and control, auxiliary sensors, sensor interpretation, and wireless communication. Examining the test results and potential concerns in scaling the prototype for a full-sized model will determine the overall success of the project. It should be noted that the idea of transferring technology was such an efficient process that the four members developed a completed prototype in less than five months while working only part-time on the project.

2 THE PROBLEM OF COLD-TRAILING

Every summer, thousands of hectares of forested land around the world are consumed and destroyed by fires. While significant firefighting efforts are required to extinguish the flames amidst the hot and dry weather conditions, much of the human resources deployed are with the goal of implementing fire-suppression techniques, beginning with fire discovery and continuing during the "mop-up stage" until all potential sources of new fires in the vicinity are completely out. These procedures include the use of *cold-trailing*, a method of determining whether or not a fire is still burning, involving careful inspection and feeling with the hands to detect any heat source, as well as with the use of infra-red scanners, either hand-held or mounted on planes and helicopters, in order to locate hotspots and thus reduce mop-up time.

Cold-trailing is a highly reviled job, yet it is the only sure way to tell whether or not a fire is actually out. It typically involves hours, days, or even weeks of exhausting labour, with crews working 14-hour days to keep a forest fire from threatening homes or valuable timber[12]. Limited resources are thus utilized for a grueling and repetitive task, and firefighters who trust their senses to locate hotspots and buried embers by running their bare hands through the ashes often run the risk of being burnt. Helicopters equipped with thermal imaging cameras have limited precision; dense cloud cover that is typical of smoke from neighbouring fires or thick underbrush common to densely forested patches can both block the infrared signals.

3 MOBILE ROBOT DESIGN

A hotspot detection robot can be designed to autonomously explore such volatile regions, relaying information on the location of potential ember sites to a control station, and generally decreasing the workload and danger that the firefighters are exposed to. As the hotspots are found, the intensity and bearing coordinates (of accuracy dependent on the resolution of the system employed) can be broadcast back to the base station via radio or other ranging techniques. This is the premise of the Autonomous Cold-Trailing Omnirange Robot or ACTOR.

The initial focus of the investigation centred on the development of a scale prototype. Among the many potential mobile robotic concepts available, a rover-based design is certainly the ideal. Consider, for instance, the similarities in the operating environments of the Martian rovers and the proposed robot in a post forest-fire scenario, as outlined in Table 1. In both cases, a robust, adaptable wheel arrangement provides mobility in rough, uneven terrain, and a variety of techniques are required to protect the robot from temperature, radiation and dust hazards. Further architecture criteria and considerations for robust Mars exploration rover autonomy are also pertinent. These include[3]:

- Robust, flexible operation, since the execution environment is comparable.
- Efficient utilization of resources such as power, communication bandwidth and data storage, to track behaviour with resource allocation.
- Self-recovery from faults or failures to increase efficiency and operating time.
- Operation amidst uncertainty, where the physical characterizations of the environment are unknown.
- Operation that guarantees safety, since the rover's objectives need to be accomplished.
- Operation with limited communication, as smoke, dense brush and trees can obscure and cloud communication.
- Operation with multiple objectives, more so when the rover would be required to put out hotspots in addition to detecting them.

Thus the direct application of the Martian rover would be exceedingly useful in detecting and mapping hotspots in the aftermath of a forest fire, serving as a safer, faster, more efficient alternative to current human-centric methods within an inhospitable environment. The parallels in operating environment and on-board architecture imply the need for similar robotic systems, as is discussed for the two scale sizes.

4 SCALE MODEL DEVELOPMENT

As with both European and American rovers, the ACTOR was broken down into five major elements – 1) its constituent *mechanical construction and control algorithms*, including the coordination of wheels or tracks that permitted mobility on rough, uneven terrain; 2) its *auxiliary sensors*, which enabled the ACTOR to perceive its environment and localize based on the grid information previously stored, 3) an on-board low-level *perception resolution algorithm* to resolve conflicting sensor data; 4) a high-level *path-planning* scheme to facilitate autonomous control over the robot's exploration; and 5) a means of *wireless communication*, to permit updates at a remote control station by notifying end-users of the location and intensity of potential ember sites, and also allowing human intervention if necessary. Additionally, a thermal imaging vision system was devised and implemented to bestow the ability to "cold-trail" on the robot. This is depicted in the top-level diagrams of Figures 1 and 2.

Table 1: Comparison of the Martian and the Post Forest-Fire Robotic Operating Conditions

	Mars	Post Forest-Fire
Terrain	Rugged terrain is littered with rocks and craters that act as obstacles.	Rugged terrain is littered with boulders, standing and fallen trees, and dense brush that act as obstacles.
Environment	Extreme temperatures average minus 53 Celsius, but range from minus 128 to plus 27.	Extreme temperatures range upwards from 60 to 100 Celsius as a result of surrounding fires in the vicinity of the cold-trailing area.
	Frequent planetary dust storms result in fine powdery grit within joints, seals and other mechanical parts.	Strong winds resulting from the high temperature differences of nearby fires blow ash and soot into firefighting machines.
Operating Distance	Extra-terrestrial application implies operation at a distance between 60 and 400 million kilometers depending on the time of year, so either high-latency teleoperation or significant on-board autonomy is required.	Removal of the human firefighting element necessitates communication to a distant base station, 1 to 100 km away, coupled with the need for dynamic location tracking and decision-making.
Radiation	The travel to Mars subjects the rover to crippling cosmic radiation and solar flares.	Heat radiation threatens the safe operation of the robot.

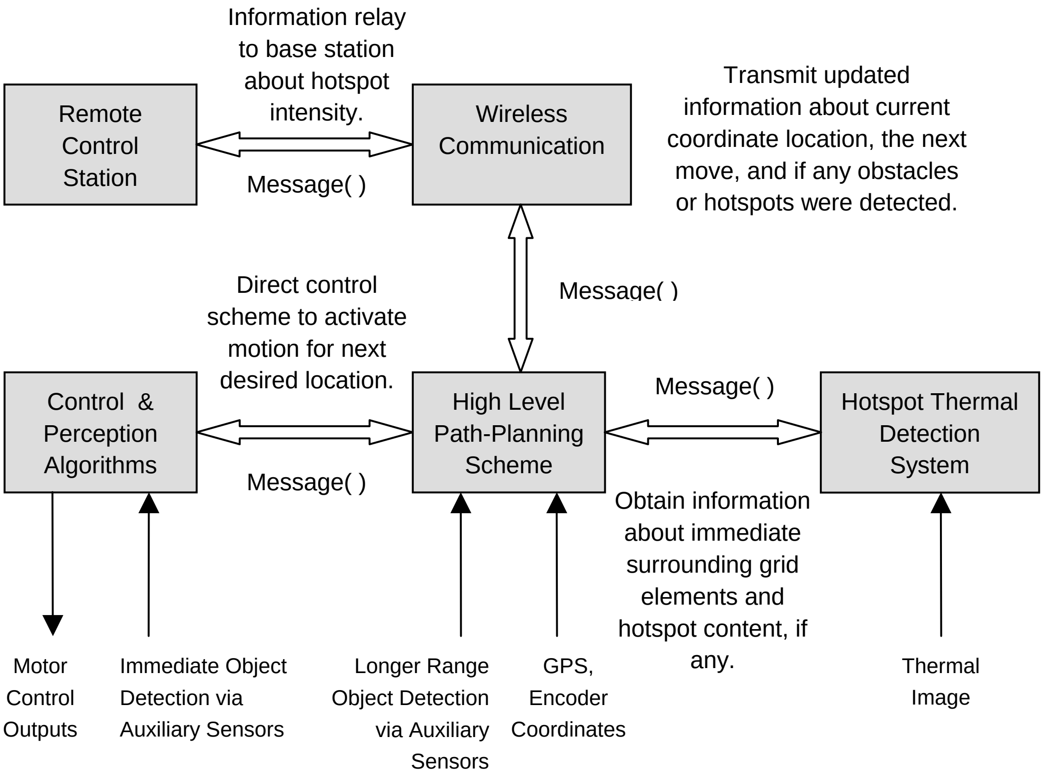

Figure 1: ACTOR subsystem interaction diagram that depicts sources and modes of environment information.

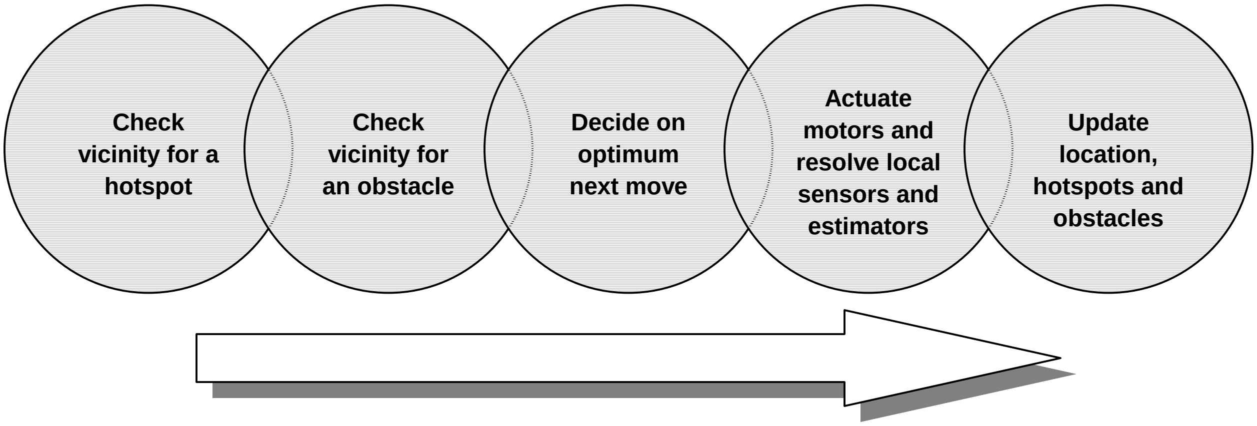

Figure 2: Process map for the scale model development of the ACTOR, demonstrating the decision flow per cycle.

4.1. Mechanical Construction and Control

Primary concerns of the mechanical construction and control of ACTOR involve a) the suspension and mobility characteristics of the robotic base, as well as the chassis requirements; b) a way of closing the feedback loop, to ensure accurate control of the mobility system, and c) ensuring the rover can withstand its extreme environments.

The most effective suspension and locomotion systems of small-scale Martian rovers can be broken down into three types: the conventional tracked system, the rocker-bogie wheeled system, and the elastic loop mobility system (ELMS). The first type is reminiscent of the standard tracked army tank, as implemented on the European tracked micro-rover "Nanokhod"[2] (see Figure 3). The second type is the kind most publicized on the Sojourner, Spirit, and Opportunity rovers, employing a six-wheeled drive platform that uses mechanical linkages without axles or springs to tackle uneven terrain. The last type, ELMS, is a novel new design employing a highly rigid elastic metal stretched between the drive wheel and the idler wheel that distributes the rover's weight evenly, as shown in Figure 4. Experiments have shown that the ELMS system is the best of the three for reducing rover-terrain "sinkage" and for achieving the longest mean free path[10]. However, tracked rovers offer performance characteristics that are very nearly comparable[4].

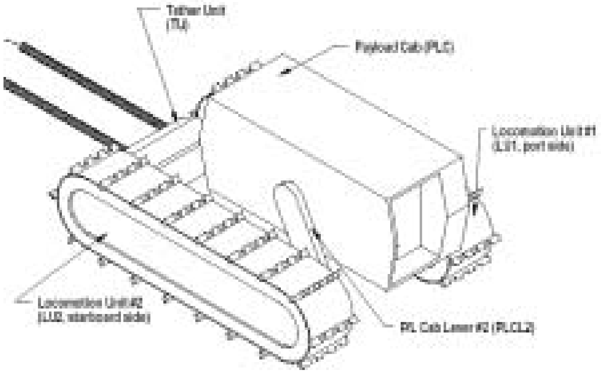

Figure 3: Isometric sketch of the European Space Agency Micro-Robots for Scientific Applications Model A Concept "Nanokhod"[2].

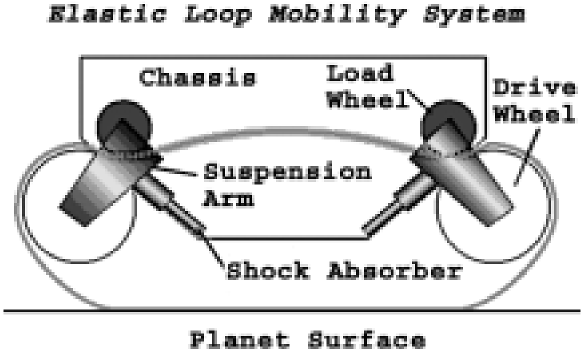

Figure 4: Illustration of an ELMS system[10].

Since the goal of the project was to demonstrate that Mars rover technology could be applied both cheaply and efficiently, even for a scale proof-of-concept model, the financial and time costs of implementing the ELMS system could not be justified. Based on the operating environment similarities, and even identical payload mass specifications for a scale prototype, the ACTOR was instead equipped with a base design similar to that of the conventional tracked system as embodied by the "Nanokhod" (compare Figures 3 and 5)[2, 11]. The design in both cases is robust, and optimally integrates a sound payload-carrying capacity with efficient locomotion and terrain traction.

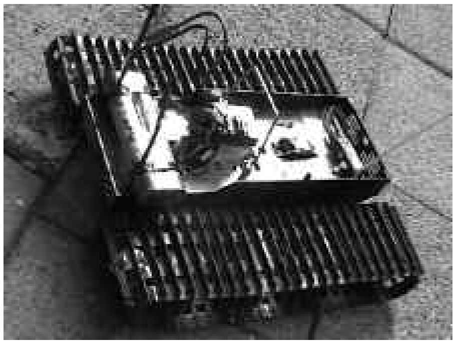

Figure 5: Photograph of the Kyosho Blizzard EV base used for the ACTOR[11].

The second concern, closing the feedback loop, requires a means of relative or local positioning. This is quickly resolved using dead reckoning odometry, a de facto standard for Mars rovers, making use of shaft encoders and a digital compass for closed-loop feedback[5]. What makes the full-scale rover similar to its Martian counterparts, and different from other mobile robots, is the planned use of GPS coordinates as an alternative to VHF radio omniranging, either from satellites in cases where the GPS signal is strong, or from pseudodolites and pseudolite arrays otherwise.

The third primary concern is building the robot to withstand extreme environments. Like all Martian rovers to date, the full-scale ACTOR can be equipped with a "Warm Electronics Box" that is insulated with silica aerogel in order to maintain temperature-sensitive components within a nominal operating range. The remainder of the physical elements must be rated to operate within extremes of 100^{o} C, and as much of the rover as possible will be encased within a sealed chassis to prevent exposure and interference by the fine sediment present in the air. This constraint was bypassed during scale-model development to facilitate rapid prototyping.

4.2. Auxiliary Sensors

The electrical design of the ACTOR involves interfacing a number of sensors in order to give the robot its "eyes" and "ears". As witnessed by the redundancy in working-class rovers – features such as nine independent cameras on the last pair sent to Mars –

functional robots require a variety of obstacle detection sensors that can correlate and corroborate with each other in order to generate a world map that closely resembles its real environment. Sonar at the front of the scale ACTOR facilitates obstacle avoidance, while subsidiary infrared rangefinders on its side allow for more efficient obstacle detection to aid in path planning. The digital compass is vital for accurate position feedback, and on-board thermistors act as emergency sensors allowing the rover to withdraw from situations outside of its maximum permissible operating temperature (if the rover is approaching an area where active fires are burning for instance). GPS tracking is the primary means for localization in the full-scale rover, but this was removed from the scaled version since the coordinates were too large for the scale in use. Localization is also achieved by indicating the relative position and orientation to ensure that all movement is in accordance with the artificial intelligence's Decision Making Algorithm through simple break beam circuits as shaft encoders (this is the primary technique for the scaled robot in order to avoid implementation of open-loop motor control functionality). The extension of the counterpart to the Martian cameras is discussed in Section 5. To some extent, this is an additional tool for obstacle detection as well.

4.3. Perception

Due to the redundancy of sensors on most Mars rovers, and because of real-life difficulties such as lens distortion, shadow, and vibration, the determination of an internal world model from the sensory data is non-trivial. Techniques pioneered at the California Institute of Technology and tested on their Rocky 7 prototype outline several approaches to solving this maximum-likelihood estimation problem[9]. Ultimately, the sensor measurements are weighted through a probability density function that take into account two terms representing those cases where a detected object is already part of the global map, or is instead a new addition[15]. Similar probabilistic confirmation mechanisms are required for the low level control of the rover during position verification, especially for the scale robot's sonar and infrared sensors. A simple maximum-likelihood estimation scheme is embodied in the position determination of these two classes of sensors, although the full-scale ACTOR can be expected to use more powerful probabilistic techniques such as Markov localization and Kalman filtering. In the interests of development time and project completion however, only the former technique was implemented.

4.4. Path Planning

The on-board artificial intelligence's Decision Making Algorithm is invoked upon startup. This code is responsible for the movement of the ACTOR through a pre-defined grid within which the rover localizes using a novel approach that was developed for the purpose, searching for hotspots while avoiding obstacles. Based on NASA's FIDO rover and the Russian rovers EVE and IARES[6], the path-planning intelligence is broken into a high-level system directing the full-size robot over long-range distances of 75 to 100m at a time, and a low-level system using a series of decision-making steps with local range maps moving in increments of 2m[1]. (These measurements were suitably scaled down for the prototype ACTOR). Figure 6 is a block diagram of the algorithm as implemented on the prototype, depicting three inputs: Terrain Evaluation via Obstacle Detection, Hotspot Detection via Thermal Imaging, and Process Overrides via Base Station messages. The outputs controlled by this algorithm include motion Forward, Backward, Left and Right, as well as the transmission of position and hotspot information. Processing of the algorithm is subject to additional stimuli received via the thermistors (heat threshold) and the other sensors outlined in Section 4.2 and perceived in Section 4.3. The response procedure and decision flow to the sensory stimuli takes place as per Figure 2.

Ultrasound and infrared sensors provide the terrain evaluation inputs. These set true or false messages, and this data is used to determine the next path to take. The image from the thermal camera is another input (more detail in Section 5), and each sampled image frame is analyzed to determine the presence of hotspots in front (left, centre, and right) of the robot. The gray-level colours of the image help determine the intensity of the hotspot.

The Decision Making Algorithm then determines the best path for the ACTOR to proceed on, subject to the inputs described. Of the four possible motions signaled (forward, backward, left, and right) at each grid location, a message containing the current grid coordinates and the intensity from the thermal camera is sent to the communications module prior to the actual motion. The algorithm also updates its internal grid system before proceeding to the new location.

For safety purposes, the scaled ACTOR never stays at a given location for more than 30 seconds, and the processing of the thermal image, grid coordinates and sensors is done quickly enough to permit this constraint. This feature further mitigates any internal temperature increases as a result of the external environment.

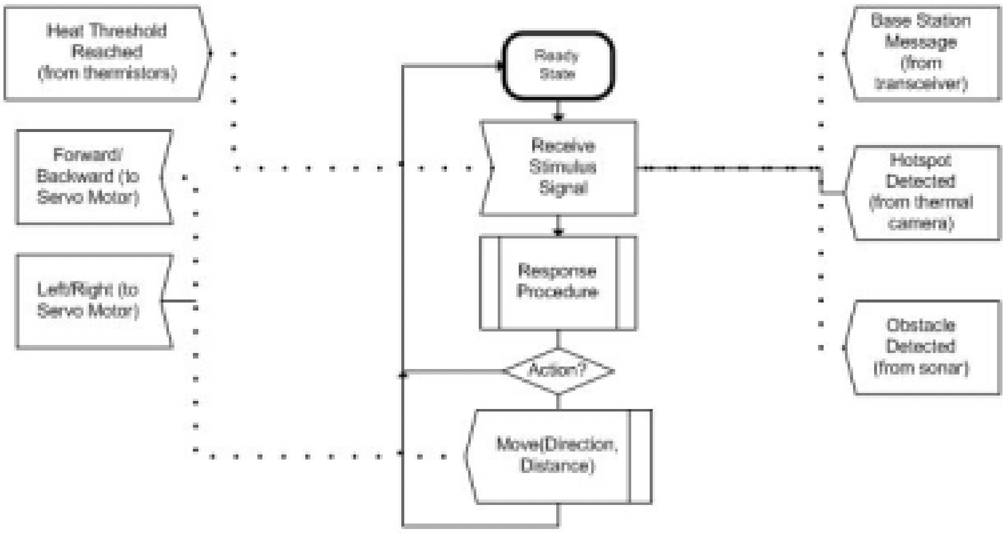

Figure 6: Software block diagram of the path-planning process.

4.5. Wireless Communication

The rover is required to relay information about hotspots back to the base station. On the recent MER rovers Spirit and Opportunity, communications with Earth occurred via a high gain directional dish antenna and a low gain omni-directional antenna in the X-band, while communication with surrounding satellites occurred through a fairly standard UHF transceiver[14]. Clearly, only the second type of shorter-range transmission is necessary in this case.

A rudimentary tool is required for the base station in order to receive and interpret data from the rover using a graphical user interface (Figure 7). A grid system displays the current location of the robot as well as any hotspots that have been detected. The system waits for messages sent by the ACTOR via the communications module, and, in the event of an emergency, has the capability to transmit manual override instructions and emergency-stop information.

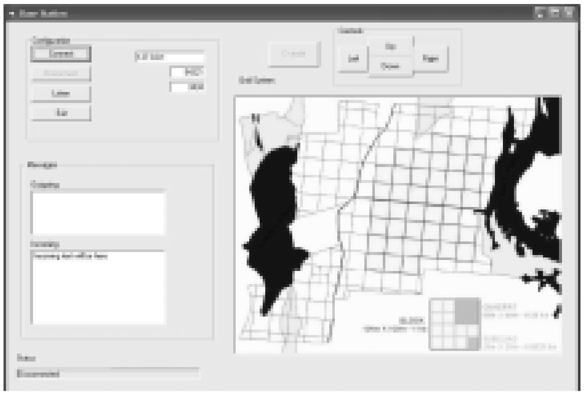

Figure 7: Base station interface controlling the ACTOR.

An on-board electrical interface is also essential to facilitate the drop-in of a standard UHF transceiver. For the full-scale model, a minimum transceiver operating distance of 5km is deemed necessary, while for the prototype, 25m is sufficient for demonstration.

5 EXTENSIONS TO THE MARS ROVER MODEL

To this point, the discussion has focused entirely on developing a mini-rover similar to those in use by the Jet Propulsion Laboratory and NASA. The following section will highlight the major feature that is necessary in order to make this robot practical and invaluable to the fire-fighting cause: a *thermal imaging vision system* that is the key for hot-spot detection.

5.1. Thermal Imaging

The primary thermal sensor in the scale ACTOR is the Thermal Eye 2000B, a thermal-imaging camera courteously provided by an external industry sponsor. This is the same camera that is used to fight fires in the U.S.A., and is of the same technology as that used by the U.S. Department of Agriculture Fire and Aviation Management. The forest's noisy environment necessitates an actual thermal camera, rather than a cheaper, passive infrared device that uses pyroelectrics or low-grade CCDs. The scaled rover must be able to distinguish objects above approximately 80°C at a safe distance of 5 m.

The software interface to the video adapter is coded in C++, making high use of the Open Computer Vision (Open CV) library available from Intel. Specifically, the Camera Calibration Toolbox stores discrete frames from the video input, and a basic hue or brightness filter is used to determine areas in the field of vision that are valid hotspots. Given the location and distance information gained from the image processing, the Thermal Imaging sub-system interacts with the artificial intelligence's Decision Making Algorithm by relaying information about its area of exploration. It identifies the area under analysis as clear, blocked, hotspot, or undefined. Figure 8 summarizes this entire sub-system.

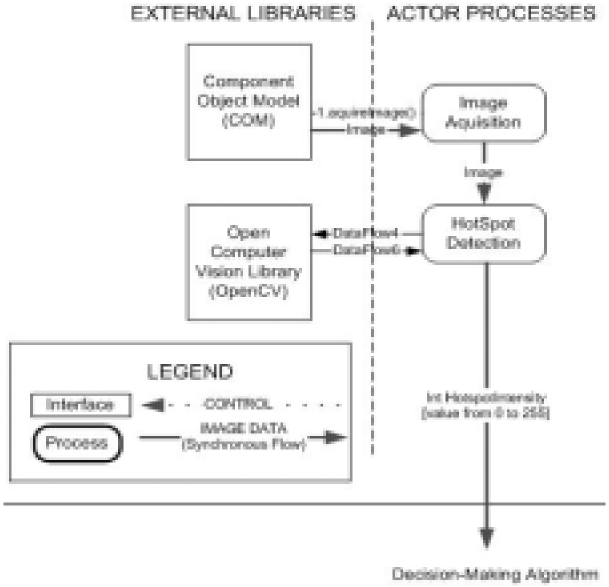

Figure 8: Process and interaction map for the Thermal Imaging sub-system.

6 FIELD TEST DESCRIPTION

To test the functionality of this first-iteration prototype model, a simulated post-forest-fire scenario was created within a lab setting. The otherwise flat surface was scattered with a small collection of stone bricks in one area of the floor, and another section was heaped with a collection of wood branches and an artificial heat source. The objective was to determine if and by how much the rover could identify and circumnavigate both the non-hazardous obstacle and the hot spot. This simple scenario is illustrated in Figure 9.

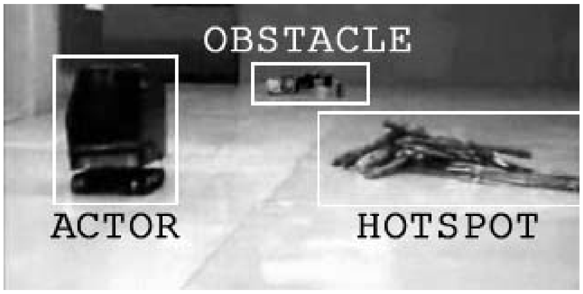

Figure 9: Image of the ACTOR test environment.

Figure 10: Close-up of the simulated hotspot.

Figure 11: Simulated hotspot rendered by the Thermal Imaging camera.

7 EXPERIMENTAL RESULTS AND DISCUSSION

7.1. Mechanical Construction and Control

The ACTOR's base design proved quite adept at maneuverability even when tried out on rough, uneven and undulating surfaces. Encoder and odometry performance was accurate to within 5% and deemed rather satisfactory. However, the initial footprint of the prototype proved too small to accommodate all the OEM components on-board, and the structural design needed to be highly vertically developed as a result. This raised the issue of overall stability, which was especially evident during turns when its rotational inertia prevented heading changes less than 45°, while each turn had an exceedingly high ±30° associated error. The electromagnetic fields issued by some of the older equipment on board complicated matters by interfering with the digital compass. Although software simulations were highly successful, the low-level control algorithm was unable to handle the extremely erratic inputs provided, and this was the major source of error in the experiment. It should be noted that a larger model, indeed even the full-scale ACTOR, would be able to eliminate all these problems. The increased footprint size does not affect the dimensions of the electronics box, and its contents can be repositioned to improve the rover's stability and electromagnetic interference.

In general, an absolute measure of the position error, e_p, of the rover can be calculated assuming the rover's heading can be interpreted:

$$\theta = \theta_o + e_\theta$$

where e_θ is a constant heading error margin from θ_o, the desired heading. In such a case, the x and y error would be dependent on the distance traversed, d, as follows:

$$e_x = d\cos(e_\theta) \quad ; \qquad e_y = d\sin(e_\theta)$$

Assuming the desired heading is 0^o, the total position error becomes:

$$\begin{aligned} e_p &= \sqrt{[d\cos(e_\theta) - d]^2 + [d\sin(e_\theta)]^2} \\ &= 2d\sin\left(\frac{e_\theta}{2}\right) \\ &\approx d\, e_\theta \end{aligned}$$

It was noted that direct track errors were roughly 7-10cm for every 2m, corresponding with a 2-3° compass heading error as per the above.

Thus, although some turning deficiencies existed as a result of the ACTOR's mechanical construction, these were limited to the scale model itself and would not be pervasive to the full-size robot. Overall, this section of the robot's design was taken to be successful since it proved that a viable design and low-level control mechanism was possible, but would need improvement.

7.2. Auxiliary Sensors

All sensors on the scale-model provided inputs within the specified boundary values expected of them. Some calibration was required for the infrared sensors since obstacles within a certain range fairly close to the sensor would instead get positioned at a much farther distance away. However, the sensor suite was considered sufficient to accomplish the desired tasks for the full version of the ACTOR.

7.3. Perception

Due to time constraints, powerful probability perception codes were not implemented on the prototype. Instead, simple one-to-one maximum likelihood mapping was implemented, based on the information provided by the sensors and the shaft encoders. While this worked exceedingly well in straight-line tracks, serious errors crept into the prototype's world models whenever turns were made, and it was only after several grid locations had passed that the robot would correctly update its position. Meanwhile, entire hotspot and obstacle locations would get incorrectly marked. On the positive side though, such errors are correctible with techniques such as Markov Localization and Kalman filtering, as well as improved mechanical performance from the full-size ACTOR. Consequently, the perception module was believed to have proved the notion that such an element is required, since reasonable performance was achieved for a subset (albeit a small one) of possible world maps.

7.4. Path-Planning

The Decision Making Algorithm worked flawlessly to the extent that it was capable of adapting and navigating a grid even when its position was changed as a result of low-level control errors. However, because of the compounding of errors at the perception level, the rover's use of the algorithm could only be tested on simple maps such as the one shown Figure 9. Again, this showed that it was possible to take elements of Mars navigational technology (the dual-decision making process) and apply them to a terrestrial setting.

7.5. Wireless Communication

No significant errors or concerns were encountered with this portion of the scale rover. Base station manual overrides were also extremely successful at controlling the robot when so desired.

7.6. Thermal Imaging

Correct identification of hotspot location and intensity occurred in 95% of all cases tried (Figure 12 is a sample). The high success rate shows that this extension to the Mars rover model is sufficient to handle the cold-trailing requirement that was the primary objective of the development of the rover.

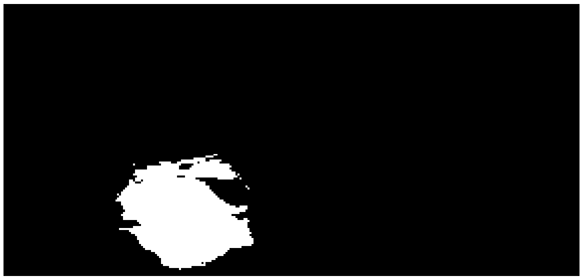

Figure 12: ACTOR-identified hotspot of area depicted in Figure 11 through blob analysis.

8 THE FULL-SIZE ROVER

The completed ACTOR would include remedies to the deficiencies identified in the previous section. A larger physical size would be better able to accommodate all electronic components, and solve one of the major issues that affected its low-level actuator control. Of course, the number and location of the components in the sensor suite would have to be changed as a result. Greater autonomy and control over its processes would be highly desirable and could be accomplished through the use of neural nets, Kohonen self-organizing maps, and back-propagation algorithms. This would permit the robot to know how to react to various obstacle and hotspot sizes and intensities, or even if a map of an area cannot be known *a priori*. More powerful probabilistic techniques for perception such as Markov Localization and Kalman filtering would be invaluable for ensuring accurate localization and positioning within a pre-specified map. Ideally the capabilities of the ACTOR could be extended to the co-operative control of multiple rovers to efficiently search for hotspots within a vast expanse of forested area. This is related to current efforts for multiple rover control at NASA's Jet Propulsion Laboratory, with their work on CAMPOUT, a Control Architecture for Multi-robot Planetary Outposts.

It can be said that the Decision Making Algorithm is not robust due to the need to pre-specify an initial world map, but this is acceptable as long as the robot is operating in a post forest-fire environment. Such environments are often charted prior to cold-trailing activity. This is again very similar to the Martian rovers in that a map is fed to the robots prior to launch, and its every move is pre-planned and closely monitored from a remote station. Although greater robustness could be imparted by asking the ACTOR to self-navigate within pre-specified bounds, such a scope is too tremendous for initial development.

9 CONCLUSIONS

It is possible to take the best design elements of various Martian rovers and incorporate them into the development of a terrestrial-based rover that can successfully operate in a similarly harsh environment. The use of these design elements can significantly shorten developmental time, especially during the build of a scale model prototype. The qualified success of this prototype indicates that a full-size version of the robot is viable and can be built once certain deficiencies identified through the proof-of-concept model can be overcome. Furthermore, the educational aspects involved in this development were tremendous – the authors completed this work as part of an undergraduate project, and made the public community (adults and children alike) aware of the success of their work through the display of the scale model and a video of its performance at a symposium.

10 FUTURE WORK

Many of the changes necessary to improve the functionality of this robot mirror the work that has been done for rovers in the field; these are techniques which were not implemented on the scale model due to the limited time and budget. A primary goal would be to validate the proof-of-concept model through a more detailed transfer of technology achieved upon further study of other Martian rovers. More efforts could be directed to the development of an alpha model of the full-size ACTOR, and upon the completion of that task, to the coordinated/co-operative control of multiple ACTORs. Lastly, moving away from the sole activity of hotspot detection to the ability to extinguish hotspots and perhaps even small contained-area fires could further extend the cold-trailing idea.

11 REFERENCES

1. Baumgartner, E. T., Leger, P. C., Schenker, P. S., and Huntsberger, T. L. "Sensor-Fused Navigation and Manipulation for a Planetary Rover." Proceedings of SPIE Vol. 3523, Boston, MA 1998.
2. Bertrand, R., Rieder, R., Van Winnendael, M. "European Tracked Micro-Rover for Planetary Surface Exploration." ESA Workshop on Advanced Space Technologies for Robotics and Automation ASTRA '98, December 1998.
3. Bresina, J., Dorais, G. A., Golden, K., Smith, D. E., Washington, R. "Autonomous Rovers for Human Exploration of Mars." Proceedings of the 1st Annual Mars Society Conference, Boulder, CO, August 1998.
4. Ellery, A. "Elastic Loop Mobility/Traction System Study for Mars Microrovers, Final Report." Technical Report, ESA, March 2003.
5. Matsuoka, M., Rock, S. M., Bualat, M. G. "Autonomous Deployment of a Self-Calibrating Pseudolite Array for Mars Rover Navigation." Aerospace Robotics Laboratory, Stanford University, Moffett Field, California, 2004.
6. Maurette, M. "Mars Rover Autonomous Navigation." Autonomous Robots 14, pp. 199-208, 2003.
7. Murphy, R. "Rescue Robotics for Homeland Security." Communications of the ACM, Vol. 47, No. 3. March 2004.
8. Nehmzow, U. "Mobile Robotics: Research, Applications and Challenges." Proceedings of Future Trends in Robotics, Institution of Mechanical Engineers, London, July 2001.

9. Olson, C. “Subpixel Localization and Uncertainty Estimation Using Occupancy Grids.” IEEE International Conference on Robotics and Automation, pp. 1987-1992, Detroit, Michigan, May 1999.
10. Patel, N., Ellery, A., Van Winnendael, M. “Elastic Loop Mobility System: The Concept And Future Prospects For Mobility On Mars.” Presented at 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ESTEC, Noordwijk, Netherlands, 19-21 November 2002.
11. Photograph courtesy Mario’s RC Models. Kyosho Blizzard. Date accessed: July 29, 2004. http://www.mariosrcmodels.com/blizzard.htm
12. Richards, G. “From Lightning Strike to Cold Ashes.” The Globe and Mail, August 26, 2003.
13. Siegwart, R., Nourbakhsh, I. “Introduction to Autonomous Mobile Robots.” MIT Press, Cambridge, Massachusetts, 2004.
14. Washington, R., Golden, K., Bresina, J., Smith, D. E., Anderson, C., Smith, T. “Autonomous Rovers for Mars Exploration.” Proceedings of the IEEE Aerospace Conference, 1999.
15. Volpe, R., Estlin, T., Laubach, S., Olson, C. Balaram, J. “Enhanced Mars Rover Navigation Techniques.” Proceedings of the IEEE International Conf. on Robotics and Automation, San Francisco, California, April 2000.

Amor Menezes graduated from the Mechanical Engineering program at the University of Waterloo in June 2005, having specialized in Mechatronics & Management Science. He is currently pursuing a Master’s degree in Aerospace Engineering as a Milo E. Oliphant Fellow at the University of Michigan at Ann Arbor, with an emphasis in Flight Dynamics and Control. His research work is in the field of Aerospace Robotics. He is also an avid pilot and a glider pilot instructor.

Rowena Luk graduated from the Computer Engineering program at the University of Waterloo in June 2005, having specialized in Mechatronics. She is currently pursuing a Master’s degree in Information Management as a Della J. Sisler fellow at the University of California at Berkeley, developing software and hardware user interfaces for information systems. She has recently exhibited kinetic contemporary sculpture in various galleries in Ontario, most notably at the international Contemporary Art Forum of Kitchener and Area in 2004.

Paul Lam graduated from the Electrical Engineering program at the University of Waterloo in June 2005, having specialized in Mechatronics. He is currently working toward a Master’s degree in Biomedical Engineering at the University of Toronto, carrying out graduate research in Human-Assistive Robotics. He is also a keen photographer and international traveler.

Ziad Bhunnoo graduated from the Computer Engineering program at the University of Waterloo in June 2005, having specialized in Management Science. He is currently working at Trapeze Software in Mississauga, Ontario, Canada, as a Software Developer and Analyst. He is also an accomplished competitive Latin dancer.