2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Autonomous Hot Metal Carrier

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Abstract— **This paper reports work involved with the automation of a Hot Metal Carrier — a 20 tonne forklift-type vehicle used to move molten metal in aluminium smelters. To achieve efficient vehicle operation, issues of autonomous navigation and materials handling must be addressed. We present our complete system and experiments demontrating reliable operation. One of the most significant experiments was five-hours of continuous operation where the vehicle travelled over 8 km and conducted 60 load handling operations. We also describe an experiment where the vehicle and autonomous operation were supervised from the other side of the world via a satellite phone network.**

I. INTRODUCTION

Vehicles operate constantly around industrial worksites. In many applications, they perform repetitive homogeneous tasks such as moving loads from one warehouse location to another. In the aluminium industry, Hot Metal Carriers (HMCs) perform the task of transporting molten aluminium from the smelter (where the aluminium is made) to the casting shed where it is turned into block products. The vehicles weigh approximately 20 tonnes unloaded and resemble forklifts except they have a dedicated hook for manipulating the load rather than fork tines (Figure 1). The molten aluminium is carried in large metal crucibles. The crucibles weigh approximately 2 tonnes and they can hold 8 tonnes of molten aluminium usually superheated to 700 degrees Celcius. Therefore, HMC operations are considered heavy, hot, and hazardous, with safety of operation a significant issue.

Our research is focused towards automating the operations of Hot Metal Carrier-like vehicles. There are many challenges in their operating environment considering they travel inside and outside buildings. Inside, there is a vast amount of infrastructure, other mobile machines and people. In various areas, there are large magnetic fields and high temperatures near the molten aluminium vats. Outside, their paths may be surrounded by infrastructure, fences, and their operation may be effected by the environmental conditions: rain, fog, snow, and heat. Research into automating these vehicles and their operations needs to consider the variability in operating conditions to produce repeatable and reliable performance of the task.

At our worksite, we have fully automated a Hot Metal Carrier and have demonstrated typical operations of a production vehicle. Our vehicle is capable of autonomous start up, shutdown, navigation, obstacle management, and crucible pickup and drop off. It has conducted over 100 hours of autonomous operations and demonstrated long periods of high reliability and repeatability. The vehicle also has several safety systems incorporated into it to make its operations as safe as possible. The remainder of this paper outlines our research and results.

Fig. 1. A Hot Metal Carrier in the process of picking up the crucible.

Section II presents the work related to automating industrial vehicles. Section III outlines the architecture and technical components of our Hot Metal Carrier's systems. Section IV provides details and performance of various experiments conducted at our worksite. Section V concludes the paper with a brief discussion of the significance of the research and future work.

II. RELATED WORK

There has been much research into automating industrial vehicles for cargo transport. [1] present a complete system for controlling autonomous forklifts in a warehouse. The forklifts are scheduled from a centralised controller and can be operated autonomously or remotely. Localisation of the vehicles is provided by a webcam sensing lines painted on the floor.

[2] demonstrate a different approach to automating vehicles by using a humanoid robot to operate the controls of a

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conventional vehicle. The advantages of using a humanoid are that the vehicle does not necessarily have to be modified to allow pseudo-autonomous operation and the robot can be used for other tasks. The disadvantages are that the current standard of humanoid technology makes controlling a vehicle overly challenging and unreliable. Furthermore, vehicle control has to be encoded in the humanoid which would be difficult for a closed loop system considering the complexity of a human conducting the same tasks.

In 1999, our research team demonstrated the autonomous operation of an underground mining vehicle, a Load-Haul-Dump (LHD) vehicle [3], [4]. This work showed that 2D scanning lasers could be used to navigate a vehicle at 20 km/h with little clearance (approximately 0.5 m) between the mine walls. The system developed worked on the principle of relative or reactive navigation where the LHD was steered based on the open space observed immediately in front of it. Higher level turning commands, such as "turn left", "go straight", etc, were issued by a navigation layer that had a coarse representation of location in the mine tunnel system. The navigator kept track of which section of tunnel the LHD was in by observing key features such as intersections. The system is now available commercially and has been deployed in a number of mines around the world.

With respect to the load handling task, and in particular, pallet handling by a forklift, several important research works must be noticed. Garibotto *et al.*, in [5]–[7] present ROBOLIFT, a robotic forklift able to pickup/drop off pallets using computer vision. This work was conducted indoors and used specially designed fiducials. In our case, we are aiming at a minimally modified outdoor setting where these fiducials may not be discriminative enough. In more recent research, Nygards *et al.* in [8] used the image of a visible laser in a camera image to localise a pallet and dock a forklift to it. After some experiments, we found that an eye-safe laser is not powerful enough to be reliably visible by a camera in bright sunlight. Finally, in [9], another method of vision-based pallet sensing was described. Again, this work was aimed at an indoor forklift, and used motion capture fiducials.

Most of the control algorithms discussed in the above-mentioned research into load handling could be applied to our crucible handling task. However, the pallet sensing methods are not suitable due to their low saliency and reliability in an outdoor, industrial setting.

It is also important to note that a number of companies (Corecon, Omnitech robotics) provide autonomous forklifts for indoor, warehouse environments. Most use laser-based solutions, mainly due to the high reliability of features detected with these sensors. But to the authors' knowledge, there is no generic, vision-based, outdoor forklift on the market yet.

III. OUR APPROACH

Our HMC has been automated to the level it can carry out all the operations of a conventionally operated vehicle with a driver on-board. However, whereas the driver of a conventional HMC is responsible for the efficiency, safety and sensing for the operations, the autonomous HMC has hardware systems to take this role. Apart from the obvious internal sensors that provide information about the state of the vehicle (e.g. temperature, oil pressure, odometry, hook height, mast tilt, etc.), the vehicle has external environment sensors to assist with navigation, obstacle management and crucible tasks. Four scanning laser rangefinders are positioned around the vehicle (Figure 2) and are tilted down to provide 360 degrees of coverage to a distance of approximately 30 m, with the blindspots apparent in the figure. These lasers are used to provide beacon-based localisation and obstacle detection. A Pan-Tilt-Zoom (PTZ) webcam (Figure 3) attached to the mast is the primary sensor for locating the crucible via markers on its handle.

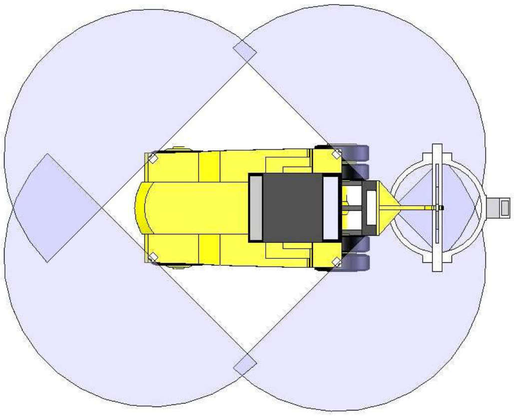


Fig. 2. The HMC's lasers are located at each corner of the vehicle and offer overlapping coverage out to approximately 30 m.

The autonomous HMC's safety system consists of a number of physical interlocks, Emergency Stops (E-Stops), obstacle management, on- and off-board RF remote failsafe and software watchdogs. The E-Stops are located around the vehicle, inside and on the portable remote RF device. Activating an E-Stop brings the vehicle to a quick halt and shuts down the engine. Hydraulic controls are frozen at this point. Door interlocks are also included in the E-Stop loop to prevent access to the vehicle whilst runnning autonomously. The software safety systems consist of high-level velocity control when objects are detected close to the vehicle and low-level watchdog checks between interface level software and the low-level control software. A timeout on the watchdog initiates an E-Stop.

Figure 4 provides a high-level view of the software and hardware architecture of the autonomous HMC's systems. Low-level components such as throttle, brakes, steering, hook and mast controls are controlled through Programmable Logic Controllers (PLCs). The critical safety components, such as the E-stop buttons and the watchdog monitor, are controlled through higher grade failsafe PLCs. These PLCs provide redundancy checks of relay connections and con-

Fig. 3. The PTZ camera used for locating the crucible.

tinuously monitor the input and output state of hardware connections.

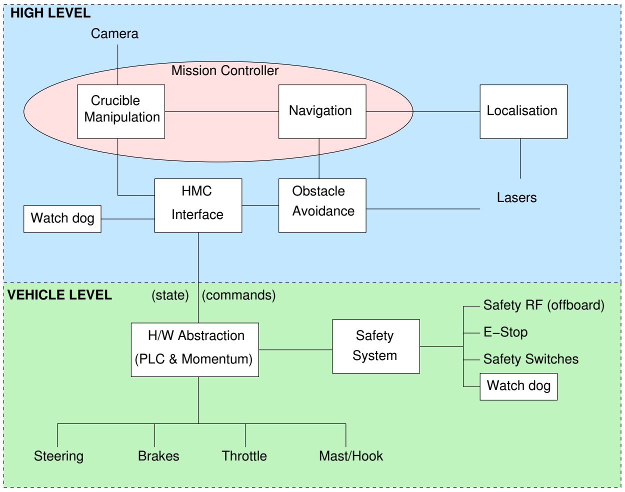


Fig. 4. The HMC system architecture. The program blocks are shown in boxes or ellipses with leaves representing physical parts of the system.

The H/W Abstraction program converts the internal vehicle state sensors to human-readable signals and manages the vehicle demands in an opposite manner. High Level programs work directly with the external sensors and vehicle state to control the vehicle. Vehicle Level programs control and monitor the vehicle hardware systems.

IV. EXPERIMENTS

The HMC has been operational for over one year and conducted more than 100 hours of autonomous missions. In this section, several experiments are discussed along with the performance evaluation of the primary high-level systems.

A. Localisation and Navigation

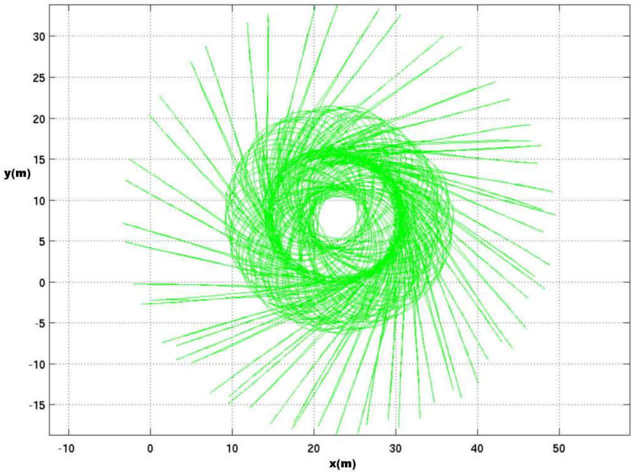
The localisation system is comprised of laser rangefinders detecting beacons placed around the environment. It uses the vehicle's encoder-based odometry as a motion reference but provides better accuracy since odometry suffers from drift and inaccuracies depending on the tyre pressures, load and road surface conditions. A full payload for the HMC weighs approximately 10 tonnes which distorts the tyres and effects odometery readings. In many applications, GPS is a useful sensor for outdoor-only operations. Differential, WAAS and RTK GPS can provide higher accuracy than normal GPS with precisions in the range of 2 cm to several metres. However, GPS accuracy depends on many factors including visibility of a significant number of satellites in the GPS constellation and a relatively clear path from the GPS and differential base stations to the vehicle's receiver. Around our worksite (and in a typical smelter), none of these factors are maintained since the vehicle operates inside and between large buildings, and around roadways surrounded by tall trees. This results in significant multi-pathing and signal loss or complete dropout in some areas. Therefore, a local, rather than global localisation solution is required.

The navigation system uses waypoints derived automatically by driving the required route of operations. Waypoints are recorded after a certain change in distance since the last waypoint or a certain change in vehicle heading. Each waypoint also contains a velocity so ramping speeds can be utilised for smoother navigation. The resulting waypoint list is split into task segments with each segment being a homogeneous action such as a forwards traverse (used for normal navigation) or backwards traverse (used for crucible manipulation tasks). Within a segment, the navigation system switches to the next waypoint in the list when it is close to the current waypoint. The mission program (Section IV-C) handles switching between tasks.

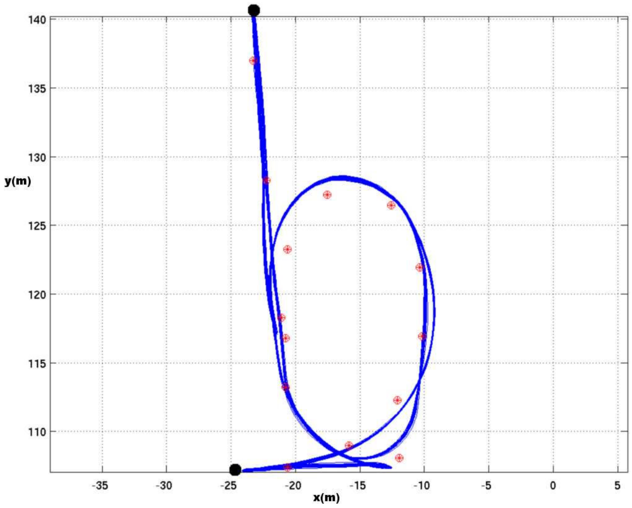
Currently, the obstacle avoidance system is simply a velocity-reduced gradient envelope surrounding the vehicle. As obstacles get closer to the vehicle, the vehicle slows and will eventually stop if they are too close. Obstacle avoidance is set for each task segment and is generally active when the vehicle is travelling in open areas. In areas where the vehicle will travel close to objects, such as entering a narrow doorway, it is disabled.

The performance of the localiser and navigation system has been evaluated and tested over many experiments. The most significant results are presented in the remainder of this subsection.

1) Long Duration: Repeatability and reliability are paramount to using an autonomous vehicle for continuous operations. We evaluated the autonomous HMC running for 5 continuous hours on a repetitive mission indicative of the typical industrial task. The HMC ran a 300 m circuit that involved picking up and dropping off the crucible two times each. It repeated this circuit 29 times in the 5 hours and covered a distance of 8.5 km. The vehicle's location was periodically recorded and the associated tracks are shown in Figure 5.



(a) Odometry track showing the effect of heading drift. The actual path is shown below.



(b) Localiser track with navigation waypoints superimposed. The large black dots represent the two locations where the crucible was dropped and picked up each cycle.

Fig. 5. The vehicle tracks over 5 hours of operation. The odometry track is locally accurate but due to the large number of left hand turns, drifted in heading significantly. The "split" between clustered localiser tracks is due to different approach and departure waypoints being used for the different segments of the mission.

The localiser track shows a high degree of accuracy and repeatability. The average lateral deviation in the track was approximately 10 cm over the entire run. The localiser performed well considering one of its inputs is wheel odometry.

2) RTK GPS Ground Truthing: To provide an accurate evaluation of a navigation and localisation system, a more accurate ground truthing method is required. This is extremely difficult to achieve logistically and realistically over the large area of the HMC's operations (in the order of kilometers around our site). During certain times of the day when there were greater than 5 satellites visible in the GPS constellation, RTK GPS provides accurate coverage over a part of our environment. This was used to evaluate the *global* accuracy of the localisation system. To obtain this data, the vehicle had to be driven at sub-standard speeds around the site and stopped whenever the RTK quality GPS lock was lost until it was regained, or a significant amount of time elapsed. Figure 6 shows a comparison between the GPS, localiser and odometry tracks. As can be seen, there is a close match between the GPS and localiser paths when the RTK lock was available. Odometry was particularly bad in this example due to dissimilar air pressures in the tyres on either side of the vehicle.

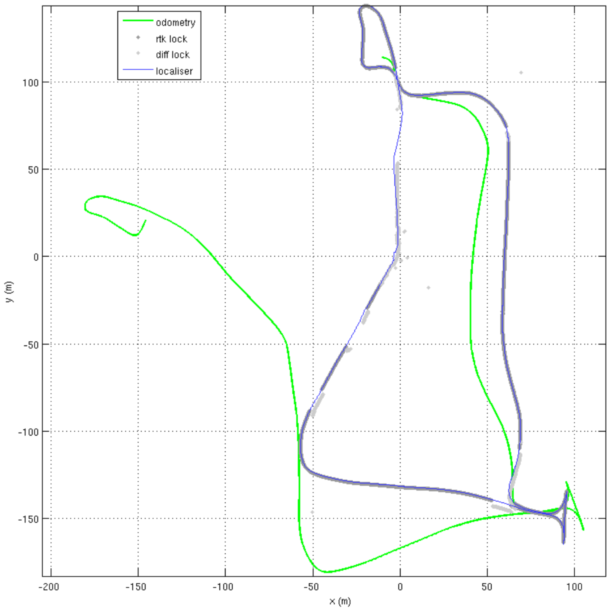


Fig. 6. Comparison between RTK GPS (grey), the HMC's localiser (blue) and odometry (green). GPS tracks are dark grey where full RTK was available, light grey where the GPS lock dropped back to differential mode and absent where GPS dropped out completely. This was most prevalent along the roadway through the centre of our worksite which is surrounded by large buildings.

Figure 7 shows the scatterplot of the accuracy of the localiser compared to the RTK measurements. The average error was 0.97 m for RTK lock and 2.8 m for differential.

B. Crucible Operations

The key functionality of a Hot Metal Carrier is its ability to handle the crucible. Two main operational phases can be distinguished: crucible pickup and crucible drop off.

a) Crucible drop off: Drop off is an easy manouver from an automation point-of-view. No sensing is required and a simple ballistic manouver is sufficient (Figure 8).

b) Crucible pickup: The pickup manouver is much harder than the drop off. It can be divided into two steps: first, an approach step where the hook is visually guided toward to the pickup point in the middle of the crucible handle (Figure 9), then the actual pickup. The latter is an easy manouver, again a ballistic movement, similar to a drop off (Figure 8).

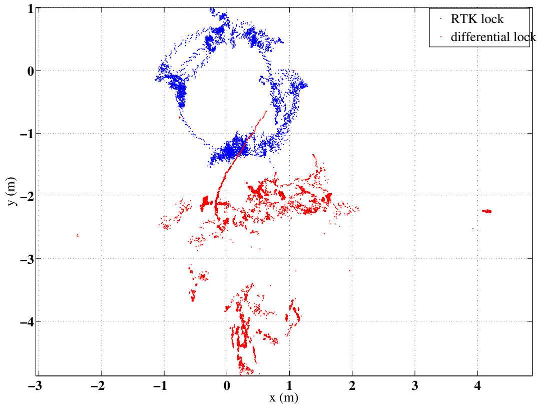


Fig. 7. The error between the localiser and RTK GPS (blue), and the localiser and Differential GPS (red) over the path shown in Figure 6.

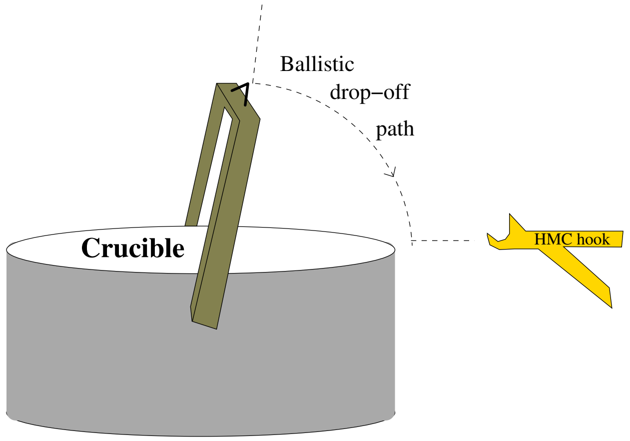


Fig. 8. Schematic of the hook movement during a drop off manouver.

The approach part is more complex. It is principally based on the onboard PTZ webcam detecting the crucible from about 5 m. As with most outdoor computer vision applications, it requires proper management of sensitivity to lighting conditions, and suffers from poor accuracy and long processing times. There are two reasons why we use sensor-based servoing and not a memory of the position where the crucible was last dropped off. First, in a real-site, several agents handle the crucible (cranes, lifts, and other HMCs). If some are not computer controlled or instrumented, there will be inaccuracies and uncertainties on the crucible drop off positions. Secondly, even during computer controlled drop off from our autonomous HMC, the crucible can swing around the hook and produce a different drop off position than previously. Most significantly, the crucible's orientation can vary in an unpredictible manner.

c) Results: Again, the reliability and predictibility of the HMC autonomous manouver is critical to its acceptance by the light metal industry. As an illustration of the repeatability of our current implementation, Figure 10 shows the superimposition of half of the 58 pickups performed during our 5 hour run. It can be clearly seen that the paths are well contained in an envelope whose width is correlated with the variation of crucible position (dots and the ellipse around the crucible handle).

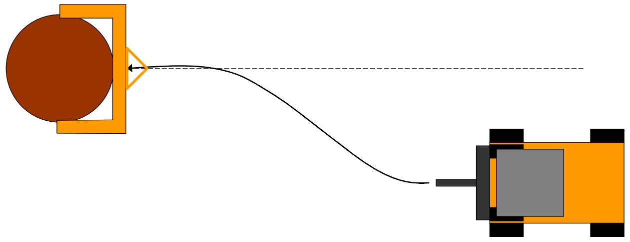


Fig. 9. Approach of the crucible during a pickup manouver.

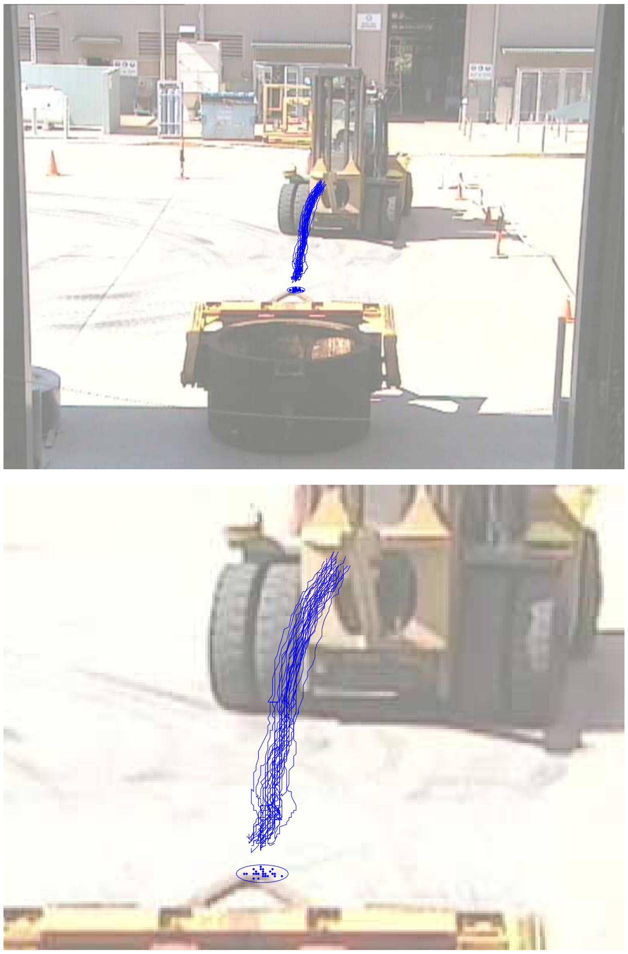


Fig. 10. Pickup approach trajectories, superimposition of 15 pickups. The dots and the ellipse around the crucible handle show the variability of the crucible location across this set of manouvers. The top figure shows an overview of the stage, and the bottom figure shows a close-up on the paths themselves. For reference, the handle width is about 2 m and the pickup hole approximately 20 cm across.

C. *Mission Planning and Recovery*

The Mission Controller is responsible for switching between tasks and monitoring their performance. Currently a mission is a sequence of tasks with each task returning its status during execution. Once a task has finished, the Mission

Controller selects the next task. Contingencies occuring during task execution cause the Mission Controller to select the contingency subtask for that task. For example, a missed crucible pickup will trigger a “missed approach” signal and the HMC will move away from the crucible and retry to pick it up. During the 5 hour experiment, the only halt in operations occurred after approximately 4 hours when the remote Safety RF unit’s battery went flat. This triggered an E-Stop on the vehicle. When the battery was replaced, the vehicle was restarted and as it was about to pickup the crucible at the time of the E-stop, it executed a missed pickup and successfully continued its operations.

D. Very Remote Control

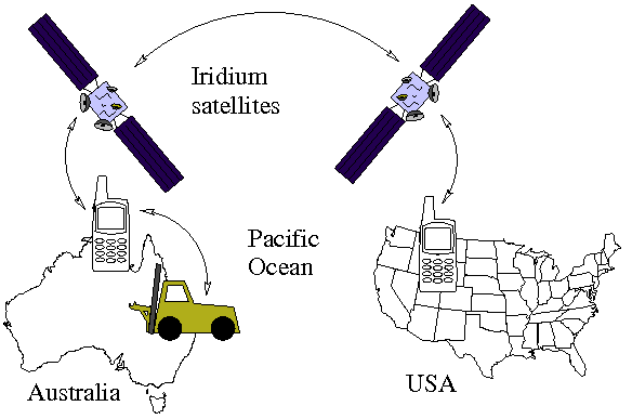


Fig. 11. Schematic of the communication setting for the Iridium-controlled HMC

The goal of this experiment was to investigate the feasibility and implications of remotely supervising HMC operations. Iridium phones were used to provide the communication medium between a remote operator and the HMC’s onboard systems. Figure 11 depicts our setup. A collaborator was sitting with a computer connected to an Iridium phone in the USA. From there, he called up the HMC’s Iridium phone in Australia, and established a networked connection through Point to Point Protocol (PPP). Once the connection was up, the state of the HMC was sent to a simple Java application on the client side. The client had the possibility to send simple controls such as “pause” or “resume”.

During the experiment, the network round-trip was recorded through a ping-like mechanism. The data is summarised in Figure 12. Two main conclusions came from this trial: first, the communication roundtrip time is high and any application wishing to implement remote control robotics using the Iridium network has to deal with this explicitly. Secondly, keeping a stable data channel up through the Iridium network was a real challenge.

Nevertheless, the experiment was a success: our collaborator overseas was able to “control” our robotic application. The experiment also provided an indication of the latencies involved with long distance tele-operation. We could keep the connection up for 30 minutes and during this time, the remote operator stopped and restarted the vehicle multiple times.

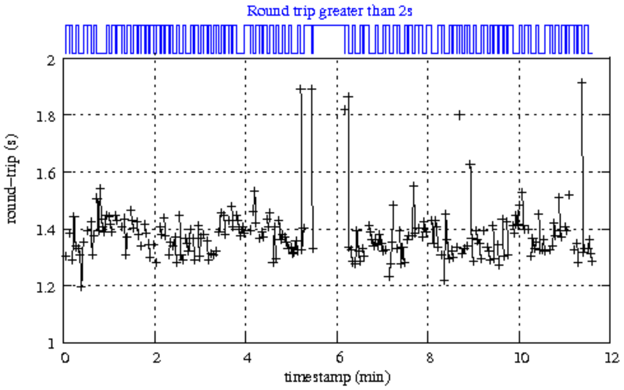


Fig. 12. Measured round trip while conducting remote controlled operations via the Iridium network, between USA and Australia. The blue graph on top is a binary signal indicating when the connection was considered lost, that is when no answer was received after 2 seconds, or an answer arrived with a roundtrip longer than 2 seconds.

E. The Effect of Rain on Operations

Hot Metal Carriers need to operate under all types of environment conditions including rain, snow, fog, hot and cold days. We have tested in wet and rainy conditions to determine the effect of rain on the external sensors, which in turn can effect task performance. So far, even in moderate persistent rainfall, there has been little change in performance. One problem encountered was a reduction in road surface traction when wet, which caused the vehicle to slip a little. This produced a slightly different track than in the dry. Reducing the speed of the vehicle in the wet helps overcome this problem but raises the question of how to adapt the vehicle’s control system to adjust for rainy conditions *before* wheel slip occurs, and how to detect wet road surfaces.

The only other rain-related problem that has occurred is with the noise that rain drops add to the laser image. Detected drops persist momentarily but can alias range readings of a single scan ray between the raindrop and a background object detected in the ray. This makes it harder to detect distant landmarks as the rain gets heavier. The SICK laser rangefinders have adjustments to reduce the effect of this noise and we will conduct further testing in summer storms for a more thorough analysis of the potential problems of heavy weather operations.

V. CONCLUSIONS AND FUTURE WORK

We have shown in this paper that it is possible to fully automate a large industrial materials handling operation — that of hot metal movement in an aluminium smelter. This was achieved by automating a Hot Metal Carrier, a 20 tonne fork-lift type vehicle. We found that GPS can not be relied upon for vehicle localisation and that a 2D laser-scanner based localiser using reflective beacons can provide the necessary accuracy and robustness in the mixed indoor-outdoor environment of a typical aluminium smelter. A crucible handling system was developed that accurately located the pose of the crucible of hot metal with respect to the vehicle (using a vision system) and then controlled the vehicle to pick it up. Results of a five hour duration fully autonomous run were then presented. This experiment is a significant achievement in field robotics as it is one of the first long duration autonomous demonstrations that has a challenging manipulation task every few minutes. During the five hour run, the crucible was handled approximately 60 times and the vehicle travelled nearly 9 km. Finally, we showed how this vehicle and operation could be supervised (and controlled at a high-level) from the other side of the world via a satellite phone network.

Future work on this project includes the deployment and testing of the system at an operational smelter and the development of other large scale materials handling applications.

ACKNOWLEDGMENTS

This work was funded in part by CSIRO's Light Metals Flagship project and by the CSIRO ICT Centre's ROVER and Dependable Field Robotics projects. The authors gratefully acknowledge the contribution of the rest of the Autonomous Systems Lab's team and in particular: Polly Alexander, Stephen Brosnan, Matthew Dunbabin, Paul Flick, Leslie Overs, Pavan Sikka, Kane Usher, John Whitham and Graeme Winstanley, who have all contributed to the project. We would also like to acknowledge the contribution of CSIRO Exploration and Mining Automation team, in particular Brendon Stichbury, Zak Jecny and Andrew Castleden, who assisted in converting our HMC to a drive-by-wire vehicle. We also greatly acknowledge the efforts of Boeing and their partners for their assistance and participation in the remote supervision experiment.

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