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Autonomous Hot Metal Carrier — Navigation and Manipulation with a 20 tonne industrial vehicle

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Abstract— **This paper reports work on the automation of a Hot Metal Carrier, which is 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. Finally, an experiment where the vehicle and autonomous operation were supervised from the other side of the world via a satellite phone network are described.**

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 carry 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. 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 repeatibility. 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.

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 system and can be operated autonomously or remotely. Localisation of the vehicles is provided by a webcam sensing lines painted on the floor. 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 [2] present ROBOLIFT, a robotic forklift able to pickup/drop off pallets using computer vision. This work was conducted indoors and used specifically designed fiducials. In our case, we are aiming at a minimally modified outdoor setting where these fiducials may not be discriminative enough. 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 forklifts on the market yet.

III. Experiments

The HMC has been operational for over one year and conducted over 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

The localisation system comprises 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 and the load. 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. 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.

a) 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 $300\,\mathrm{m}$ circuit that involved picking up and dropping off the crucible twice. It repeated this circuit 29 times in the 5 hours and covered a distance of $8.5\,\mathrm{km}$. The recorded localiser track shows a high degree of accuracy and repeatability. The average lateral deviation in the track was approximately $10\,\mathrm{cm}$ over the entire run. The localiser performed well considering it uses wheel odometry as a guide.

b) 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. We conpared the accuracy of the localiser 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. 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 the pickup point in the middle of the crucible handle, then the actual pickup. The latter is an easy ballistic movement, similar to crucible drop off.

C. Very Remote Control

The goal of this experiment was to evaluate the feasibility of controlling a robot via the Iridium satellite communication network. A collaborator was sitting with a computer connected to an Iridium phone in the USA. From there, he was able to monitor the state of the application and send simple controls such as "pause" or "resume".

IV. 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 with respect to the vehicle using a vision system and then controlled the vehicle to pick it up. A five hour duration, fully autonomous experiment was 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 60 times and the vehicle travelled nearly $9\,\mathrm{km}$. Finally, we showed how this vehicle and operation could be supervised 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.

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