CHAMP: a Bespoke Integrated System for Mobile Manipulation

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***Abstract*—Mobile manipulation is a robotics paradigm with the potential to make major contributions to a number of important domain areas. Although some mobile manipulators are commercially available, bespoke systems can be assembled from existing and separate mobile, manipulation, and vision components. This has the benefit of reusing existing hardware, at a lower cost, to produce a customised platform. In this paper we introduce CHAMP, the CSIR Hybrid Autonomous Manipulation Platform, and describe the required integration of a Barrett Whole Arm Manipulator, a PowerBot AGV, and the necessary sensors. The described integration includes both the hardware and the software.**

I. Introduction

Mobile manipulation, the subspecialty of robotics concerned with the close coupling of navigation and manipulation, has exploded in popularity in recent years. This has largely been driven by decreasing hardware costs (particularly in sensors and actuators), and the proliferation of the online open-source software community. The effect is a wide and increasing range of robotics applications, where robots are able to interact with their surroundings without being fixed to a single location. It is through these capabilities that robots may finally realise their full potential in domains such as healthcare and rehabilitation, search and rescue, and assisted living.

Over the last few years, several robotics manufacturers have responded to the changing state of research, software and hardware, and have commercialised mobile manipulators. However, a number of research labs have developed their own such robots, typically through the combination of simpler devices (see Section II for a review of both commercial and lab-built platforms). These in-house designs can be constructed to fulfil a wide range of requirements, and are often comprised of simpler off-the-shelf robots [1].

This paper documents the assembly of CHAMP (CSIR Hybrid Autonomous Manipulation Platform), a lab-built robot for research into autonomous mobile manipulation. This system includes a single manipulator, the Barrett Whole Arm Manipulator (WAM) [2], with seven degrees of freedom and a sturdy four wheeled base (two active, two passive) with differential drive (the PowerBot AGV [3]). The robot is equipped with an additional computer for control and sensory processing, as well as several visual sensors. The complete system was assembled entirely in-house.

This paper addresses the design considerations and decisions for building the aforementioned mobile manipulation system. Although the requirements for such a platform differ between research groups, the basic integration processes and procedures should remain common to similar projects.

Although complete off-the-shelf mobile manipulation systems are available, assembling a mobile manipulator in-house provides the benefit of increased flexibility in platform design. This additionally results in the reuse of existing hardware with the effect of considerably lower costs compared with purchasing new equipment. Furthermore, there are a range of existing different designs varying in size, capabilities, and constituent parts from which to draw inspiration. This paper makes a contribution to the lab-assembled mobile manipulator literature.

This integration project involved both hardware and software components. As realised with the hardware, software reuse was also a high priority. Included is a review of both the mechanical and electronic aspects of the hardware integration, and then the software issues ranging from low-level controllers to ROS (Robot Operating System) integration, and finally interfaces for operator control.

This paper is structured as follows. In Section II we provide a summary of mobile manipulators, both as off-the-shelf solutions and bespoke integration projects, and their functionality as it relates to our system. An overview of the CHAMP system is then presented in Section III. After briefly outlining the specifications of the constituent robots used in the build in Section IV, we proceed to discuss the details and process of the hardware and software integration of this platform in Section V. Finally, concluding remarks are presented in Section VI.

II. Mobile Manipulators

Recent hardware developments in cost effective 3D depth sensing, initiated by Microsoft's Kinect, and continued exponential growth of computing power, has led to a proliferation in the number of commercial and lab-built robots which range considerably in design. We focus here specifically on mobile platforms with wheels as opposed to legged designs, such as Honda's Asimo [4] and ATLAS (based on Petman [5]) from Boston Dynamics, which have very different hardware and control considerations. We further consider three classes of robot systems: complete off-the-shelf mobile manipulators, custom built systems not commercially available, and bespoke platforms that were assembled from other robots. Although there are many robotic systems available in all of these categories, focus is placed on the most prominent in this review.

One of the first, and most iconic, commercially available mobile manipulators was the PR2 (Personal Robot 2), developed by Willow Garage and made available for research in 2010 [6]. The robot has two manipulator arms each with seven degrees of freedom (DoF) mounted in an upright frame on a wheeled base, and complemented with a rich suite of sensors. It was released as the flagship of the ROS open-source architecture and is commercially available, currently being used at over 30 institutions around the world. A smaller single-armed variant, the UBR-1 from Unbounded Robotics [7], was expected to address the problem of the high price tag of the PR2, although it is currently unclear if this platform will reach the market.

Another commercial mobile manipulator is the KUKA youBot [8]. This robot is available with either one or two manipulator arms, each being a 5 DoF arm with a two-finger gripper, mounted on an omni-directional four-wheeled base. It should be noted that the maximum reach of the youBot arm is less than one metre above the ground, whereas the PR2 can comfortably operate on surfaces 1.5 m high. The Care-O-Bot 3 [9], developed by Fraunhofer IPA, is another commercially available single-arm mobile manipulation system on omnidirectional wheels. It features either a Schunk Lightweight Arm 3 (LWA-3) or the Kuka LBR, both of which are 7 DoF arms. A second low DoF "manipulator" is a carrying tray which doubles up as a touch screen interface.

We next consider research platforms that have been developed in-house by a research or development lab, primarily for purposes of research within that lab.

One of the early examples of a mobile manipulator was WENDY (Waseda ENgineering Designed sYmbiont) [10], built at Waseda University in 1999, as a two-armed system on a wheeled base. The most recent incarnation of this robot, TWENDY-ONE, consists of a humanoid torso on an omnidirectional base. The robot has two 7 DoF arms, with a shoulder height of just over 1.1 m. Each hand has 13 DoF.

The uBot-5 [11] developed at UMass Amherst is an 11 DoF mobile manipulator. It consists of two 4 DoF manipulator arms, each roughly 0.5 m long. The arms are mounted on a two wheeled dynamically stable base, controlled by active stabilisation. A similar platform is Golem Krang [12] from the Georgia Institute of Technology, which also consists of two Schunk LWA-3 arms on a dynamic balancing base. This robot additionally has four degrees of freedom in the torso to simulate human upper body movement, and can autonomously stand from horizontal rest.

NASA's Robonaut [13] (and successor Robonaut 2) was designed for dexterous manipulation in space. It has been through a number of incarnations, having been mounted on a four-wheeled base, a two-wheeled Segway Robotic Mobility Platform, as well as legs. Both of the Robonaut's arms have 7 DoF, with each hand having 12 DoF.

The ARMAR family of robots (the most recent of which being the ARMAR-IIIb) [14], [15] from the Karlsruhe Institute of Technology are anthropomorphic bodies on holonomic wheeled bases. This robot also features two 7 DoF arms, each with a simple parallel-jaw gripper.

DLR developed Rollin' Justin [16] as a humanoid robot with two manipulator arms on an adjustable four-wheeled base. Each arm is a DLR Light Weight Robot III (LWR III) arm with 7 DoF, and each hand is the 12 DoF DLR Hand II. The torso of the robot is also based on LWR technology. The mobile platform has four wheels, each of which can extend individually. The shoulder height of this robot is 1.6 m when the torso is upright.

The final category of mobile manipulators are those systems which were assembled almost entirely from other commercially available robots. This typically involves the incorporation of one or more manipulator arms onto a mobile base, although we note that one of the earliest robots loosely described as a mobile manipulator was Shakey [17], developed between 1966 and 1972 at the Stanford Research Institute which, lacking an arm, manipulated objects by pushing them around the environment.

HERB 2.0 [18] from Carnegie Mellon University is a bimanual manipulator, consisting of two Barrett WAM arms mounted on a vertical frame. This in turn is mounted on a Segway RMP mobile base, as well as a rear caster. Each arm has 7 DoF, with an attached Barrett hand.

UMAN [19], the UMass Mobile MANipulator also uses a 7 DoF Barrett WAM, with a three-fingered Barrett hand. The arm is mounted on modified Nomadic XR4000 mobile base having four caster wheels. The wheels are dynamically de-coupled to provide holonomic motion. An older robot of similar design was the Stanford Assistant Mobile Manipulator (SAMM) [20]. SAMM also consisted of a holonomic Nomadic XR4000 base, but had a PUMA 560 manipulator arm equipped with a parallel-jaw gripper.

TUM-Rosie [21] from the Technische Universität München has two 7 DoF KUKA lightweight LWR-4 arms, each with a four-fingered DLR-HIT hand. It also features a Schunk Powercube pan-tilt head. Mobility is provided by a mecanum-wheeled omnidirectional platform.

STAIR 1 (STanford Artificial Intelligence Robot) [22] featured a Katana 6M-180 arm on a Segway RMP-100 base. Its successor, STAIR 2, instead used a Barrett WAM on a custom-built two-wheeled base.

There is thus a considerable range of different mobile manipulation platforms that has been developed, both for commercial and research purposes. Although several excellent platforms are currently available for purchase, they are typically accompanied by a hefty price tag. On the other hand, engineering such a system from scratch requires extensive electrical and mechanical expertise. We have instead drawn inspiration from a number of institutions, and opted to assemble a platform from other robot components.

The design of CHAMP, as detailed in Section III, consists of mounting a Barrett WAM and Barrett Hand on a PowerBot AGV, having observed the extent to which the WAM has been successfully used on numerous mobile manipulators. A similar integration was proposed by Carnegie Mellon University [23].

It is noted, however, that few details of the physical integration are available. To this end, a full description the assembly of this platform appears in this paper.

III. System Overview

CHAMP relies on an Adept MobileRobots PowerBot AGV for mobility, and a Barrett WAM for manipulation. An outline of the specifications for both of these platforms is given in Section IV. Vision for navigation is largely provided by a forward-facing Hokuyo laser scanner, whilst a front mounted ASUS Xtion PRO supplies both colour and depth information to assist manipulation. The complete system can be seen in Figure 1.

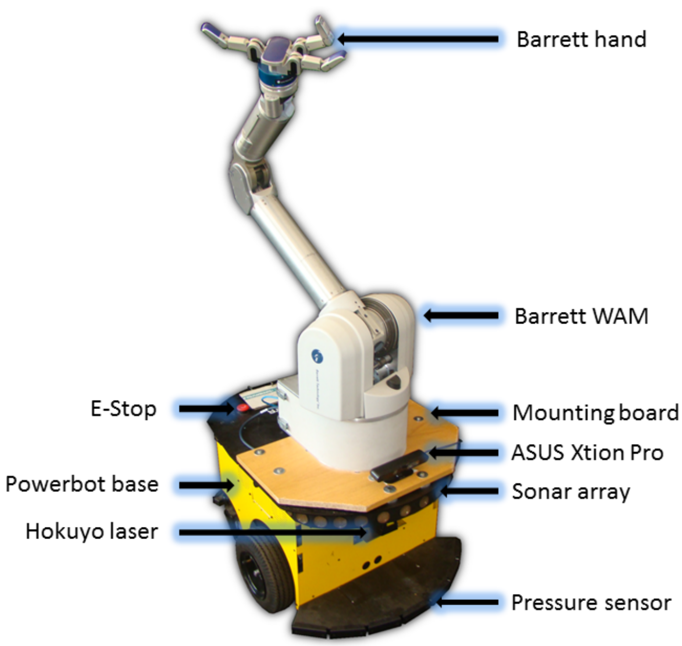

Fig. 1. The CHAMP mobile manipulator

The resulting integrated platform has a reach of about 1 m, from a shoulder height of about 0.83 m, allowing it to manipulate objects placed on standard desks and tables, as well as reach door handles, elevator buttons, etc. It has a top speed of 6 km/h, and the arm has a three-fingered hand which can lift a payload of 2 kg. The entire system has a battery life of approximately 2–3 hours.

The autonomous manipulation capabilities of the platform are largely enabled by the ASUS depth sensor. This provides the manipulator with the ability to avoid obstacles and approach objects of interest. A depiction of the field of view of the sensor is shown in Figure 2, visualised in simulation in RViz.

Although the ultimate aim and development goal of the CHAMP mobile manipulator is for it to be used in a variety of tasks under autonomous operation, the platform has also been configured for manual control. This is done by means of joystick teleoperation from an external operator's console which connects wirelessly to the platform. More details of the software integration which enables this process are provided in Section V-B.

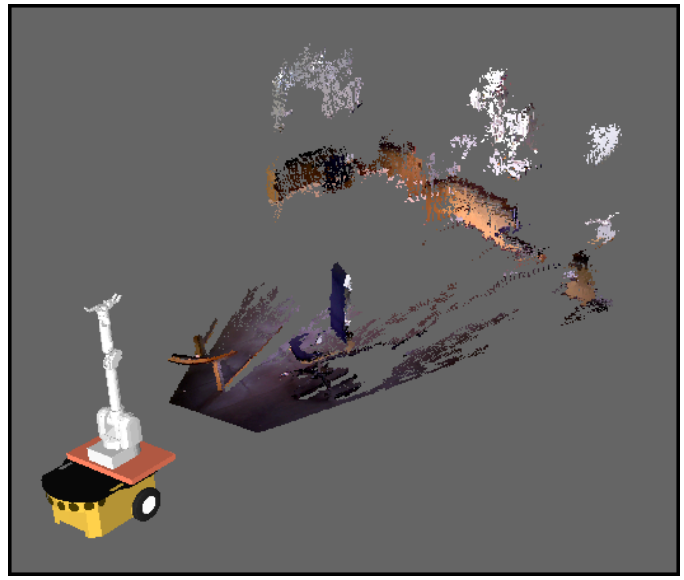

Fig. 2. CHAMP simulated in RViz, with the coloured point cloud generated from the front mounted depth sensor viewing a lab environment.

The integration process was divided into three phases. The first phase was to ensure independent operation of the PowerBot mobile base and the WAM. The second phase focused on establishing communication between all hardware components without physical integration, such that they were operated from a single computer. The third phase involved physically mounting the arm on the base, and integrating all independent software. The integration procedure is detailed in Section V-B.

IV. Constituent Robot Specifications

We now briefly describe the relevant specifications and characteristics of the two primary components of the build, i.e., the PowerBot and the WAM.

The Adept MobileRobots PowerBot AVG is a 0.9 m $\times$ 0.66 m $\times$ 0.48 m mobile base, which can transport up to 100 kg of payload at a maximum speed of 6 km/h [3]. The robot consists of a sturdy aluminium body built around a steel frame, and mobility is provided by two 0.263 m diameter wheels each driven by high-powered, independent, reversible DC motors. Two smaller caster wheels are situated at the rear of the robot for balance.

The PowerBot has two sealed lead-acid batteries wired in series to provide a total of 2,112 watt-hours at 24 V of DC power when fully charged. The batteries are situated at the rear of the robot. The battery life depends on the configuration of accessories and degree of motor activity, but under typical conditions the platform can be expected to operate continuously for at least two hours [3].

The primary default sensors of the PowerBot is an array of 24 sonar transceivers which provides almost 360^o of range sensing. The platform is also equipped with front and rear bumpers, which automatically signal the platform to halt all motion when any contact (as pressure on a bumper) occurs, provided that the contact was detected by the bumper in the current direction of motion. The base additionally has two emergency stop buttons, and once pressed these disable the motors (until re-enabled by the user).

The PowerBot is driven by the open-systems Advanced Robot Control and Operations Software (ARCOS) as the robot's controller. Client software is also provided in the form of the Advanced Robotics Interface for Applications (ARIA) [24], which is a C++ development library for interfacing with the controllers.

The Barrett WAM is a 7 DoF aluminium arm, actuated by means of a cable-driven system, and as such is back-drivable. It is considered a light weight arm, and operates with low friction. Under conditions where no external torque is applied, the DC power requirements are 27 W [2]. With a typical payload of 2 kg the power required rises to 45 W, although the maximum possible draw is 800 W.

On the end of the WAM is a BarrettHand BH8-280 [25]. This end effector features three fingers, each consisting of two joints. The fingers actuate by opening, closing, and spreading radially around the palm. The motion of the fingers is coupled, but torque-controlled to permit flexible grasping.

The WAM is equipped with two emergency stop pendants which when triggered will initiate a resistive breaking collapse of the arm. This ceases operation of the motor controllers, resulting in the unactuated WAM slowly falling with its own weight under gravity.

The WAM is controlled by an AMD Duron 1.8 GHz processor, running Linux. Base drivers developed by Barrett are installed on the WAM's computer for control of the arm. This signals are transmitted to the hardware by means of an internal CAN bus system.

V. Integration Process

A. Hardware Integration

The hardware integration was divided into two main steps. First, the components of the PowerBot base were modified by adding sensors and an on-board computer. The arm was then mounted. An important consideration which drove this division was the clear need to minimise the number of times the arm was added to or removed from the configuration, as these tasks require multiple people. Future work involves incorporating a sliding mechanism into the mount, to simplify this procedure. The internal modifications on the PowerBot are shown in Figure 3.

The first major change to the internals of the PowerBot was to install a Mini ITX computer into the base. This was to serve as the primary processing unit for controlling navigation, manipulation, sensor processing, and communication with an external operator. In order to power the Mini ITX computer from the two 12 V batteries (in series) of the PowerBot, we used a DC-to-DC converter to step the 24 VDC down to 12 VDC.

While modifying the internal components of the robot, it was important to ensure that they would be easily accessible after the arm had been mounted. Standard access to the electronics of the PowerBot is through the hinged top plate. To circumvent this access restriction following the mounting of the arm, we rearranged the internals such that the side access hatch could be used as the primary means of reaching the on-board computer. This further required the removal of an internal intersecting metal plate (situated on the left-hand side of the platform, close to the left access hatch on the left side). As this was not a load-bearing plate, this removal had no structural ramifications for the robot, but enabled easier access to the computer. Finally, a USB extension hub was included to ensure that a screen, keyboard and mouse could be easily attached to the Mini ITX if required, again with access from the side hatch.

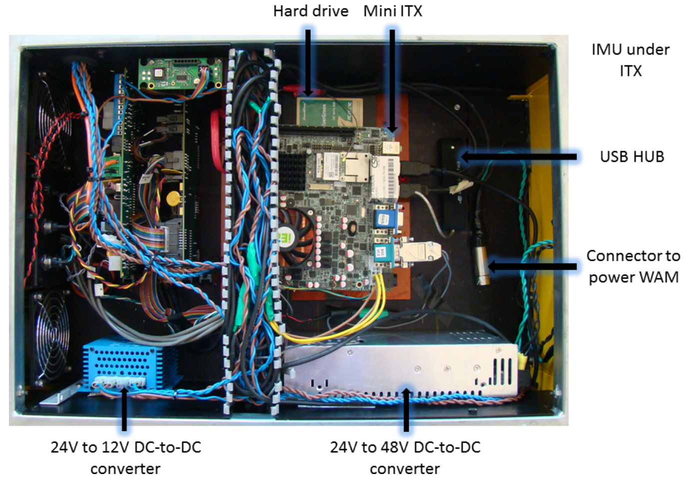

Fig. 3. The internal modifications made to the PowerBot electronics

In order to measure acceleration, angular velocity, and orientation for improved localisation, a Microstrain 3DM-DX3-25 Inertial Measurement Unit (IMU) was mounted in the PowerBot. This was situated in the middle of the base, underneath the Mini ITX.

The PowerBot base was augmented with a Hokuyo 30LX laser range scanner, which was mounted onto a bracket in the front of the base. The ASUS Xtion PRO [26] was added as a second sensor. Although these sensors are sufficient for the current instantiation of CHAMP, these could easily be augmented later through the aforementioned USB extension hub.

The WAM was mounted above the base, with its centre of weight slightly forward of the main wheels. As can be seen in Figure 1, the WAM was not attached directly onto the base itself, but rather to a wooden mounting which was bolted to the base. The depth sensor was also secured to this board, positioned in front of the arm, for an unobstructed view of the arm's workspace. The board was attached to the front half of the steel top cover of the PowerBot, yet raised slightly above it with washers. The resulting gap allowed power and Ethernet cables to be safely passed through a hole in the steel plate to the WAM without damage. The wooden board also provides the ability to remove the arm from the base while keeping it in the same position relative to the depth camera.

The Barrett WAM requires 48 VDC for operation. In order to supply the required power to the arm, another DC-to-DC converter was installed in the base to convert the 24 VDC provided by the batteries to the 48 VDC needed by the WAM. An Ethernet cable was used for communication between the Mini ITX computer on the PowerBot and the on-board computer of the WAM. This allowed the entire robot to be controlled by the Mini ITX of the PowerBot.

We finally note that changing sensors, moving the internal components, and mounting the WAM all caused changes in the weight distribution of the PowerBot, with the effect of a pronounced forward leaning of the platform. The robot was levelled by adjusting two screws at each of the front wheels to change the tension in the springs, which affects the inclination of the base.

B. Software Integration

The software infrastructure used for the low-level operation of CHAMP is shown in Figure 4. This illustrates the interaction between controllers of the two robot subcomponents, the sensors, the localisation and navigation units, and potentially a human operator.

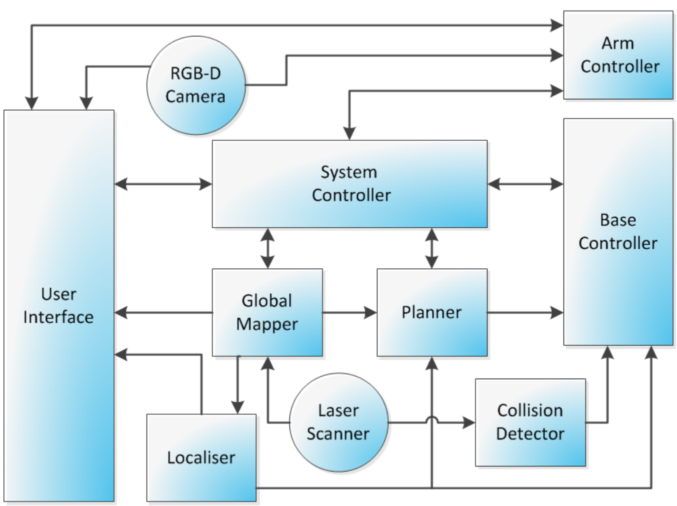

Fig. 4. The CHAMP software infrastructure. Rectangles represent code modules, and circles represent sensors.

At the core of the software infrastructure is the *system controller* subsystem. It is responsible for interfacing the different control and planning modules. It also coordinates the construction of local and global maps, the generation of goals, and executes instructions from the user interface. This subsystem also handles the e-stop switch.

The robot hardware is directly controlled through two primary subsystems: the *arm controller* which handles manipulation, and the *base controller* for navigation.

The *arm controller* is primarily based on the ROS MoveIt! stack [27]. Given a goal from the *system controller*, this incorporates the Open Motion Planning Library (OMPL) [28] for path planning, as well as OctoMap [29] as a representation of the free and occupied space in the local environment as received from the *RGB-D camera*, for obstacle avoidance. Alternatively, the arm can be directly controlled by the user from the *user interface*.

The *base controller* receives a navigation path from the *planner* and executes the appropriate control on the base hardware, reporting feedback to the *system controller*. This is supported by several other subsystems. The *collision detector* interfaces with the *laser scanner* to identify potential collisions, and perform dynamic obstacle avoidance. The *global mapper* incorporates the input from the *laser scanner* with a SLAM algorithm [30] to map the environment into drivable regions, obstacles and unknown areas. The *localiser* fuses this map with readings from the IMU to provide pose estimates of the robot. The *planner* combines all this information with a goal from the *system controller* to determine a feasible navigation path.

Primary sensing capabilities are provided by the *laser scanner*, and the *RGB-D camera*, which relies on the ROS OpenNI drivers.

Finally, user intervention is possible through the *user interface* subsystem. This provides the user with the ability to switch between manual, semi-autonomous and autonomous control modes for either the arm or the base. The user can also provide goals for semi-autonomous operation, and furthermore start or stop the robot. Additionally, this subsystem provides the user with full visualisation of the robot and its sensing capabilities within its environment, an example of which is shown in Figure 2.

VI. Conclusion

This paper introduced CHAMP, the CSIR Hybrid Autonomous Manipulation Platform, a mobile manipulator assembled by mounting a Barrett WAM to an Adept MobileRobots PowerBot AGV. This was driven by the need to create a mobile manipulator, whilst reusing existing hardware and thus reducing costs. This reuse extended the value and possible applications of the existing hardware, and provided a greater degree of flexibility in the personalisation of the platform.

This paper describes the integration steps taken in the development of this robot, both from a hardware and a software perspective. The combination of these two off-the-shelf robots, with the incorporation of range and depth sensing capabilities, has resulted in a fully-functional multi-purpose system, which is wholly compatible with a community of open-source software and suited to a diverse range of applications.

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