An Integrated Design Towards the Implementation of an Autonomous Mobile Robot

John Mallon, Ovidiu Ghita, Paul F. Whelan
Vision Systems Laboratory, School of Electronic Engineering
Dublin City University, Dublin 9, Ireland
Ph: +353 1 7005869, Fax: +353 1 7005508
{*john.mallon,ghitao,paul.whelan*}*@eeng.dcu.ie*

Abstract— **This paper details the design and implementation of a wheeled mobile robot, which will be referred to as Mobius (Mobile Vision Autonomous System), for self-sustained indoor operation. Its rugged design enables it to be easily customised with auxiliary equipment providing a wide application base. This is facilitated by an accurately controlled high power drive system, with onboard power and computational sources, giving much improved performances and capabilities comparable to that of commercially available devices in the same price bracket. The mechanical and electrical design of the robot are presented, optimised for cost and performance. The remainder of the paper concentrates on the design and implementation of an accurate drive controller.**

Keywords— **Autonomous mobile robot, Mechatronic design, Digital motion control.**

I. Introduction

In recent years the area of mobile robotics has become a very active topic of research. This is fueled by recent advances in computer and sensor technologies and the potential applications offered to the manufacturing and service industries by mobile robotic systems. These include security applications such as building surveillance, operation and investigation in hazardous environments and aiding the impaired or partially impaired [1], [2], [3]. A mobile vehicle or platform is a fundamental experimental tool for research and applications in mobile robotic fields. We present a solution to the real problem of designing and implementing a general purpose experimental indoor mobile platform, named Mobius (Mobile Vision Autonomous System) shown in Fig. 1.

As robot design involves the interlinking of many traditionally independent disciplines, a modular approach has been adopted for the integration of mechanical, electrical, hardware and software components of the robot. In order to interact meaningfully with its environment the robot must exhibit autonomous behavior. The design of the robot therefore strives to capture the essence of autonomy by ensuring all necessary resources for high level operations are contained onboard the rig. These include a power system and a computer in the form of a standard desktop PC (CPU: 750MHz, RAM: 128Mb), thus avoiding the requirement of linking with an offboard supervisory computer or power terminal.

Mobius is designed as a general purpose experimental device which will be customised for a specific application

Fig. 1. Mobius in its operating environment.

with a range of peripheral equipment and sensors [4]. Low cost commercial mobile robots, circa 1000 Euro can be limited in their expansion capabilities due to low power, structural design, size etc. Our system offers a cost effective yet adaptable and expandable alternative to commercially available mobile units in the same price range.

II. Chassis design

The successful operation of a mobile robot depends primarily on the configuration of its drive system. The design draws on established principles from the fields of kinematics and control of mobile robotic systems, to endow the platform with a high degree of controllability and mobility on flat indoor surfaces [5], [6]. A robot that exhibits controllable behavior can follow any xy path in any direction θ over a plane. Such a robot is omnidirectional and is capable of motion with three degrees of freedom, two translational and one rotation [7]. For many tasks however, omnidirectional motion is not necessary. A robot with one degree of

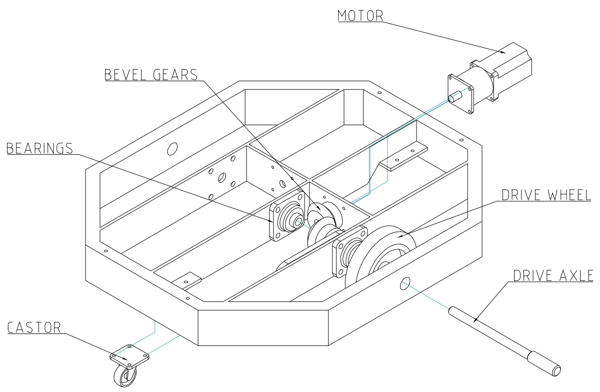

Fig. 2. The internal supporting structure of the chassis into which the drive components are assembled.

translation and one degree of rotation can follow a path in any direction by first rotating around its axis to face that direction. Mobius is given locomotion by two diametrically opposed drive wheels similar to [8]. Two unpowered vertically compliant castor wheels are used for balance and to ensure the drive wheels maintain constant contact with the ground. The base outline of the robot is circular as this configuration offers the best compromise between the overall external size and the available internal area. The mechanical setup of the drive is optimised to eliminate all external forces on the motors thus ensuring that maximum torque is transmitted while also improving the lifetime of the motor bearings substantially. The drive is housed in the base of the chassis, arranged in such a fashion so as to minimise the internal configuration space.

The chassis design is shown in Fig. 2 and Fig. 3. The outline section of the base is formed using a non-regular octagonal approximation to a circle. This is used as the manufacture of a circular base involves incremental bending of the section into shape or casting, both of which involve specialised procedures and increase cost. A hexagon resolves these difficulties and can be manufactured using standard processes. The ribs are formed using flat stock to minimise space and allow the drive components to be entirely housed within the ribs of the base section. A plate is inserted into the tapered cutaway section of the center rib at each end to support the castors.

In order to maintain a compact modular design the robot's components are housed on a level architecture. The base section is therefore used as the first level. Heavy items such as the power supply are placed here in order to maintain a low center of gravity. A second level is used to accommodate the onboard computer system while a third level is provided for sensor mounting. The levels are formed using a detachable frame as shown in Fig. 3. Four upright struts are used to form the supports for each level. The base of the final level consists of a rigid octagon shaped polycarbonate sheet as illustrated in Fig. 1.

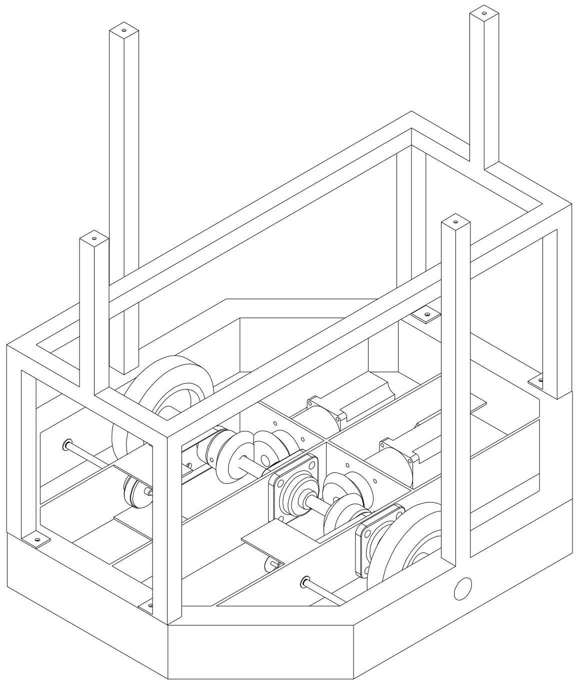

Fig. 3. Model of assembled drive and chassis components.

III. Electrical systems

A computer system is a primary component in allowing a robot to operate autonomously. Its functions include supervision and management, which can be performed by on and off board computers. To remove the tie between the robot and off board resources, an onboard standard desktop PC (CPU: 750MHz, RAM: 128Mb) is used to fill both roles. This allows the device to operate in a self-contained mode as well as eliminating transmissions. The choice of computer system is application dependent, however an intelligent robot must be capable of sensory perception, motion control, reasoning about the state of its environment and planning accordingly. Mobius is designed to be used in conjunction with various sensors to perceive its environment, including a stereo head [4], which places a high demand on processing power. Also with the evolution of general computing power, the robot is designed to carry and support a commercial off-the-shelf PC architecture, without requiring any modifications.

The power requirements of the robot are presented in Table 1. Power sources are an inevitable challenge in the design of all mobile systems. Two 12V gelled acid batteries rated for 25 Ah are used, giving an average operation time of 5 hours. They offer a safer alternative to conventional lead acid batteries and exhibit deep cycling abilities. The computer is powered using an inverter which generates 250 Vac. This is advantageous as it allows the use of the PC power module, preventing us from designing an ultimately costly DC-DC power distribution system for the computer. This modularity allows fast setup and is an overall optimised solution.

TABLE I

Static and dynamic specifications of the developed robot.

Dimensions	(mm)
Wheel Diameter	150
Base	693 x 593
Height	610
Ground Clearance	35
Mass	(Kg)
Total mass	61
Computer system	10
Motors	3.5
Chassis	30
Batteries	16
Components	1.5
Power requirements	(W)
Computer system	60
Drive system	25
Operating time	$\simeq$ 5hrs
Max translate speed	100 cm/s
Max acceleration	154 cm/s^2
Translate Resolution	0.56mm
Turn Radius	0mm
Rotate speed	$260^o/s$
Rotate resolution	0.2^o
Payload	30Kg

IV. Drive system

Torque for the drive system is provided by two geared hybrid stepping motors, developing 5 Nm pullout torque with a step resolution of 1000 steps/rev. They offer a cost effective alternative to DC servo systems at this scale and can realise controlled behavior easier, within their bandwidth. They are driven by a current controlled driver responding to a clock input signal in the range of 0-1800 Hz to control the speed and a boolean direction signal.

Robot positioning or localisation within an environment is the first issue to arise in many mobile robotic systems. Many partial solutions can be roughly categorised into relative position measurements and absolute position measurements [9]. Traditionally, localisation is achieved by the fusion of one or more methods from each section. Odometry is the most widely used method for relative positioning of a mobile robot. It has inherent advantages in that it relies on simple geometric equations [10], [6] and sensors, but the fundamental disadvantage lies in the accumulating nature of the measurement errors, which are outlined in [11]. To this end Mobius is fitted with two low cost incremental phase-quadrature encoders [12] for odometry. The sensor signals cannot be used directly for odometry purposes, but must be integrated in order to track the wheels rotational position. This decoded data is used to calculate the current position and to provide feedback on direction, position and velocity to the drive.

An important advantage of using stepping motors is that they exhibit predictable open loop responses. Due to system dynamics certain internal and external factors prevent us from utilising the system in an open loop configuration. These intrinsic dynamics are primarily due to backlash effects of gearing, and can be compensated for by a closed loop system using encoder feedback. However, feedback encoders are subject to two main limiting factors. At low velocities they produce excessive jitter which can register false counts, but these effects can be removed with a digital delay filter. Encoders also have a bandwidth within which they can detect disturbances. This is set simply as the maximum encoder resolution. Any perturbations of smaller magnitude than the encoder resolution gives rise to an unbounded error accumulation. Considering the kinematics of the robot these errors can adversely affect path tracking. To minimise these deviations we exploit the accurate open loop capabilities of the drive. Additionally, individual control of each drive wheel is highly desirable as it allows any planer motion to be executed. The most practical way of achieving this is to use two controllers. Again the open loop abilities of the controllers are used to prevent a mismatch between each other which can easily cause path deviations.

A. Controller Implementation

Closed loop control using incremental encoders can be performed by various means. Applicable methods make use of a counter to decode and integrate the encoder data into two thousand counts per revolution with associated direction. A computer samples the counters and generates the control commands to the drive amplifiers (direction and speed). This method is advantageous as it allows any control sequence to be written in software, however it also requires the continual attention of the CPU, executing mainly rudimentary functions. Also, using a multitasking operating system we cannot ensure a constant sampling rate, causing the digital closed loop to have a variable bandwidth and possibly get oscillatory. These factors significantly diminish the performance of the system so this control strategy was not adopted. An efficient solution is implemented using two low cost dedicated digital motion controller IC's [12] to execute the digital control algorithms for each motor, thus freeing the host processor from the time intensive tasks of motion control, see Fig. 6. They provide an interface between the incremental encoders and a higher level computer architecture. In addition other important functions are provided, including closed loop position control, closed loop velocity control using a proportional or proportional/integral control strategy, and for odometry, 24-bit positional monitoring. The new commands for each motor are computed by the host processor, i.e. the final position, velocity and acceleration, using simultaneously acquired positional data. The controller can then apply classical trapezoidal position profiling using this data to complete the move. This device is used on many commercial mobile robots such as TRC's Labmate and Helpmate [13].

The motors are driven using the standard stepper interface, to take advantage of availability and the modu-

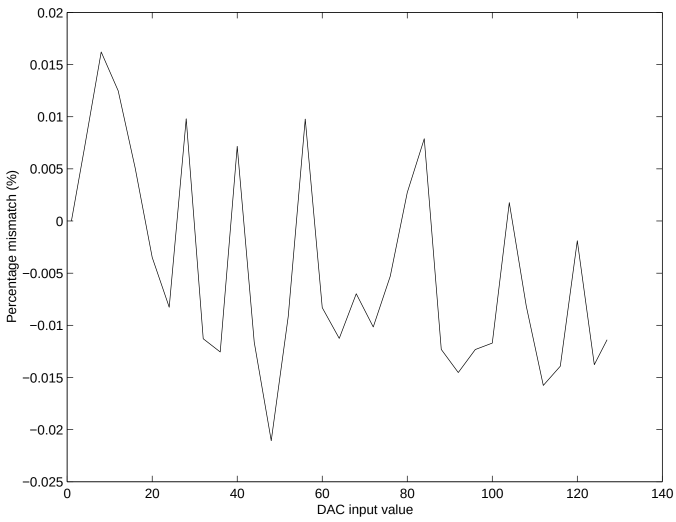

Fig. 4. Percentage frequency generator mismatch between the two controller channels.

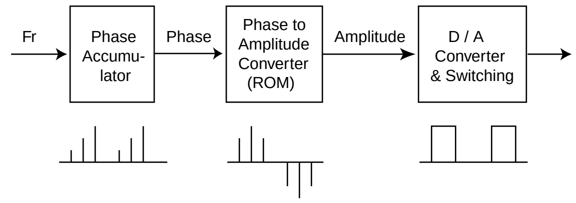

Fig. 5. Simplified block diagram of the direct digital synthesiser with signal flow.

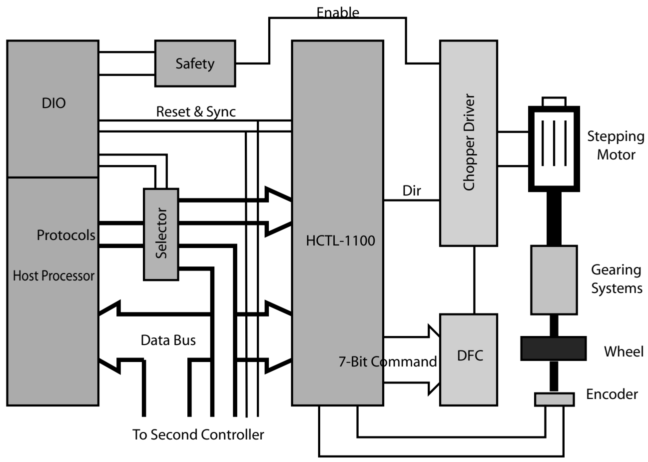

Fig. 6. Block diagram of the interfaces to the HCTL-1100 controller.

larity they offer. The drivers operate using a frequency speed control and directional signal. The controllers also offer a standard interface as an 8-bit, 2's complement port, connected to the internal digital control loop. This configuration is commonly interfaced using *voltage controlled oscillator* (VCO) tuning circuits [14], utilising a DAC and VCO combination as a frequency generator. This combination can achieve a typical linearity of 0.01%. Also, due to the circuits environment this linearity degrades further. These degradations are primarily due to noise induced from various sources and component environmental dependencies. Fig. 4 shows a snapshot of the percentage mismatch between both frequency generators, measured over their operating range of 0Hz - 1800Hz. This linearity level gives rise to a 0.56mm/s deviation from the desired path, which is unacceptable for accurate control. Note that these deviations cannot be removed using a closed loop as they are outside the encoder bandwidth.

Our implementation, however, guarantees sub-hertz frequency matched accuracy between both controller channels. This is achieved by generating the speed control signals using *direct digital synthesis* (DDS), proposed in [15]. The DDS architecture is illustrated in Fig. 5. The input frequency control word (F_R) is used to drive a phase accumulator. A ROM look up table converts the phase information into values of a sinusoidal wave. A DAC is used with some switching to generate the output frequency. This approach renders an entirely digital system free from noise, component drift and tolerances. It also maximises the open loop performance which in turn complements the closed loop system. The resulting drive is free of the stiff calibration procedures involved in standard VCO tuned methods. Fig. 6 shows a block diagram of the optimised controllers.

V. Experimental results

To assess the system characteristics, the platform was tested in a known environment. Specifically of interest is the system mobility under dynamic operating conditions, and its static and dynamic stability. Mobility is directly linked with the robot's mass ($61kg$) and the drive system capabilities. The platform exhibits high acceleration at $154cm/s^2$ and a maximum translational speed of $100cm/s$ and is insensitive to the normal dynamics of operation, indicating the drive power is correctly scaled. Each drive wheel has a translational resolution of 0.56mm guaranteed by an accurate control system. The maximum rotational speed is $260^o/s$ with a corresponding resolution of approximately $0.2^o/s$.

An assessment of the controllers matched characteristics are shown in Fig. 7. This shows the difference between the two encoder positions over a 30 second period, with a common command speed of 85cm/s. As shown the difference between the encoder counts during this time varies by ± 1 encoder count. Considering that the encoders are mechanically operated devices, small misalignments are common, resulting in slight velocity oscillations which cause position oscillation. Fig. 7 shows a 1 position count oscillation artifact. Note also that the sampling is not synchronised with the encoder velocity, giving a random appearance to the data.

VI. Conclusion

In this paper we describe the integrated design and implementation of an indoor wheeled mobile robot. The robot offers a low cost, yet high performance, adaptable system with the ability to be expanded for a wide range of applications. The system is designed to minimise cost at

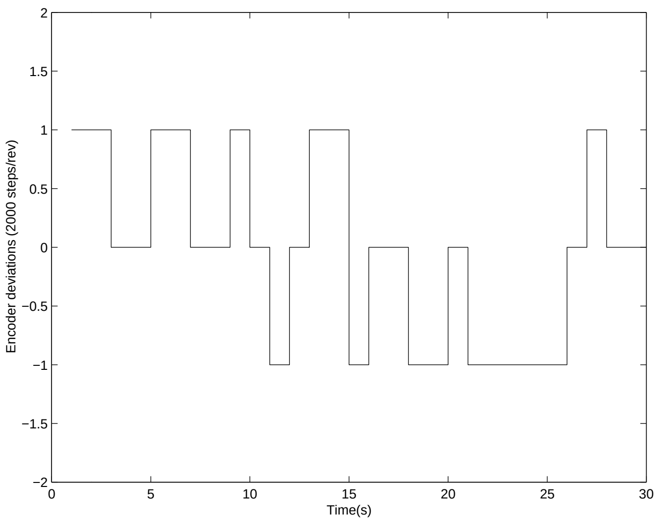

Fig. 7. Encoder data returned from straight line drive command.

about 1000 Euro, while simultaneously using high quality components. Some factors that must be considered in this are: that there is an increased cost associated with once off production and that no in-house manufacturing was carried out. The drive controller allows individual and accurate control of each drive wheel, allowing the robot to traverse any desired path. Highly accurate control is achieved using a complementary open and closed loop optimisation technique to compensate for natural component limitations. The robot's high performance specifications combined with its low cost makes it an ideal tool for a research environment.

References

[1] B. Nickerson et al. The ark project: Autonomous mobile robots for known industrial environments. *Robotics and Autonomous Systems*, 25:83–104, 1998.

[2] J. Buhmann et al. The mobile robot rhino. In *Proceedings of the Fifteenth National Conference on Artificial Intelligence*, pages 31–38, Menlo Park, CA, USA, 1998. AAAI Press/MIT Press.

[3] R. Volpe, J. Balaram, T. Ohm, and R. Ivlev. The rocky 7 mars rover prototype. In *Proceedings of IEEE/RSJ International conference on Intelligent Robots and Systems*, November 4-8 1996.

[4] O. Ghita, J. Mallon, and P.F. Whelan. Epipolar line extraction using feature matching. In *Proceedings of the Irish Machine Vision and Image Processing conference*, pages 87–95, National University of Ireland Maynooth, 2001.

[5] P. J. McKerrow. *Introduction to robotics.* Addison-Wesley, 1991.

[6] P. F. Muir and C. P. Neuman. Kinematic modeling of wheeled mobile robots. In *Proceedings of IEEE International Conference on Robotics and Automation*, pages 1315–1317, 1987.

[7] D. S. Kim, H. C. Lee, and W. H. Kwon. Geometric kinematics modeling of omni-directional autonomous mobile robot and its applications. In *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, April 2000.

[8] R. Hollis. Newt: A mobile, cognitive robot. *Byte 2(6)*, pp 30–45, 1977.

[9] J. Borenstein, H.R. Everett, L. Feng, and D. Wehe. Mobile robot positioning - sensors and techniques. *IEEE Journal of Robotic Systems*, 14(4):231–249, 1995.

[10] A. Kelly. Essential kinematics for autonomous vehicles. Technical Report CMU-RI-TR-94-14, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, May 1994.

[11] J. Borenstein and L. Feng. Measurement and correction of systematic odometry errors in mobile robots. *IEEE Transactions on Robotics and Automation*, 12(5), October 1996.

[12] Agilent Technologies. General purpose digital motion control. http://www.semiconductor.agilent.com.

[13] H.R. Everett, J. Borenstein, and L. Feng. *Sensors and Methods for Mobile Robot Positioning*, chapter 1, page 15. University of Michigan, 1995.

[14] V. Manassewitsch. *Frequency Synthesizers, theroy and design.* Wiley, 2nd edition, 1980.

[15] J. Tierney, C. Rader, and B. Gold. A digital frequency synthesizer. *IEEE Transactions on Audio and Electroacoust*, AU-19:48–57, Mar. 1971.