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DESIGN OF A SPHERICAL MOBILE ROBOT AND ITS CONTROL ELECTRONICS

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Abstract: This paper describes a type of mobile robot with a spherical shape designed to act as a platform to carry sensing devices or actuators in an environment where the conditions are harsh and the stability of the mechanical platform is critical. A remotely controlled internal unit drives the spherical robot. The paper focuses on the design and motion study of the spherical robot and on its controlling electronics. The developed electronics are implemented in digital programmable logic devices, recurring to a hardware description language. The digital hardware developed controls multiple devices: a multi-channel AD Converter, a pair of RF modules and four R/C Servos.

Keywords: Mobile robots, Programmable logic controllers, Robot dynamics, Robot kinematics, Spherical Robot.

1. INTRODUCTION

When developing mobile robots for difficult environments, typically encountered in missions outdoor, mobility is one of the central issues. There are many kinds of mobile robots that have legs, wheels, crawlers, or their combination for locomotion. However, there is the need to contrive more efficient and versatile locomotion mechanisms adaptable to an up heaved or bumpy path. This paper presents a possible next-generation mobile robot that can achieve many kinds of unique motion, such as all-direction driving and high-speed running over obstacles or rough ground without great loss of stability. The adopted structure for the robot presented in this paper was the one of a spherical mobile robot, which can be seen in figure 1.

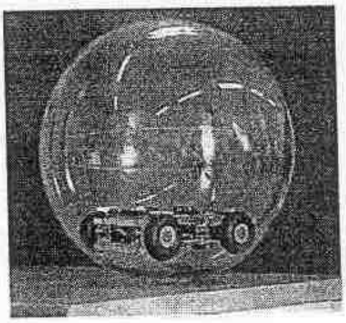

Fig. 1. Prototype of the spherical robot

Similar work with spherical mobile robots has been developed by a few other authors, but most of them are still in a phase of perfecting their system. (Bhattacharya and Agrawal, 2000) use the principle of angular momentum conservation. Two mutually perpendicular rotors placed inside the spherical shell, cause the shell to rotate in response to their own rotation. This robot proved to be fairly accurate in following a trajectory in a plane.

A different approach is to cause an unbalance in the robot by displacing its gravity centre; in turn, the gravitational force causes the robot to rotate in order to restore its equilibrium. (Halme *et al.*, 1996*a*) and (Halme *et al.*, 1996*b*) propose a robot with a single wheel resting on the bottom of the spherical shell. This construction proved to be well suited for obstacle crossing and moving in rough terrain.

(Koshiyama and Yamafuji, 1993) presented a robot including two internal pendulums used for displacing the robot's gravity centre. The robot was able to run over obstacles at high-speed maintaining a great stability. However, it was not able to move in all directions at all times since it had an external support sticking out the spherical cover for the purpose of carrying small objects.

This paper also focuses on the electronics used on the robot. In recent years have been developed new technologies for programmable logic devices (PLDs) and divulged practical Hardware Description Languages (HDLs) along with advanced logic synthesisers for those languages, which has made possible and relatively easy, to fit many systems into a single PLD. In this work, it was taken as a challenge, to use PLDs, whenever possible, in building the robot's electronics. This decision means an extra effort compared to the solution of using a microcontroller which already has many functions integrated, but on the other hand it allows for a greater control over the hardware function and for this particular case it was a cheaper solution since all of the required material was already available in the laboratory. In this work, the adopted HDL for description of the hardware function was the IEEE standard VHDL[1] for which are many available tutorials as for example (Ashenden, 1990).

This paper describes the critical steps in the project of a spherical mobile robot and its control. In section 2 the mechanical structure is presented, and a generic kinematical and dynamical model is obtained in section 3. Section 4 is devoted to the robot's construction and instrumentation so that it can perform basic surveillance tasks. In section 5 the focus is on the control electronics and its architecture. Section 6 shows some of the results obtained with the first prototype followed by a discussion on limitations of this spherical robot in section 7. In section 8 are presented ways to improve this prototype and future work needed to attain a reliable and robust mobile robot configuration.

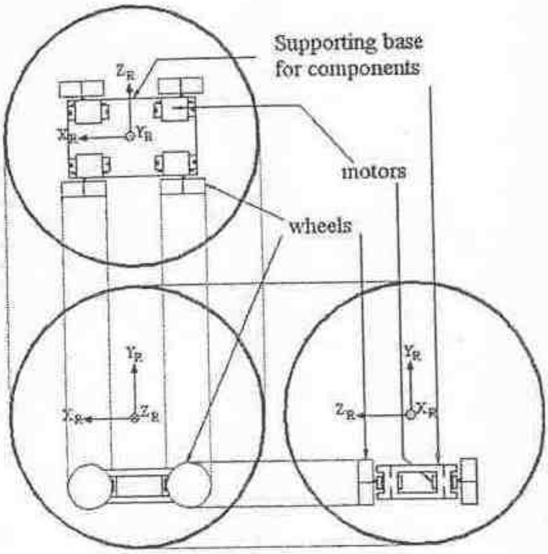

Fig. 2. Structure of the *internal unit*

2. THE SPHERICAL ROBOT

The mobile robot presented in this paper has an external spherical shape. It consists of a spherical capsule with an *internal unit* that causes the robot to roll, therefore inducing motion on the robot. The spherical capsule, which has a diameter of 40cm, is made of transparent plastics in order to allow visibility from inside the sphere as well as radio connection between the *internal unit* and the outside world.

One of the most important decisions during the designing process of this spherical robot concerns the type of *internal unit* used to induce motion of the spherical robot. Different options can be used and, in this paper, it was chosen one from the ones described in previous section.

Since the principle of angular momentum conservation is not well suited for irregular terrain where unexpected external momentums can easily appear, the solution adopted for this paper was similar to the one from (Halme *et al.*, 1996*a*). Instead of using an internal vehicle with just one wheel, it was adopted one resembling a small four-wheeled vehicle so as to have an *internal unit* of easy construction. The projected *internal unit* can be seen in figure 2, its dimensions are 20cm(l) x 16cm(w) x 7cm(h). Its high symmetry is intentional and tries to prevent kinematical and dynamical modelling errors caused by the possible turning over of the unit inside the spherical shell. The symmetry in turn of the vertical axis also makes the robot have its support base levelled when in rest.

Combining the spherical geometry of the robot with a "pseudo"-differential drive configuration for the *internal unit* the robot achieves ver

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[1] VHDL – VHSIC (Very High Speed Integrated Circuits) Hardware Description Language. A language for description of electronic digital systems, born from the VHSIC program of the United States Government, initiated in 1980. Later was adopted as a standard by the IEEE.

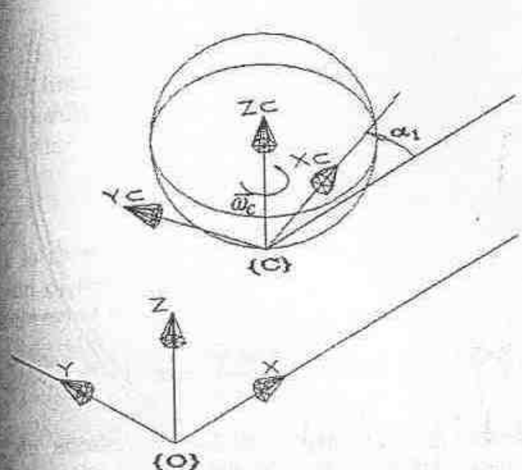

Fig. 3. Motion on a plane

interesting motion properties that allow it to behave like a holonomic robot.

In order for the spherical robot to move in a predetermined way, a control unit is needed. In the following section, a kinematical and dynamical model is determined with the goal of supporting the control unit.

3. MOTION MODEL

A basic motion analysis for the spherical robot can be easily performed using techniques similar to other fields of robotics and explained in many textbooks as for example (Craig, 1989) and (Paul, 1981). In the following paragraphs it will be developed the kinematics of this device.

Consider the contact point between the spherical robot and the plane, as shown in figure 3. This point moves and describes a continuous trajectory in the plane. An inertial coordinate frame {O} is attached to the surface and another coordinate frame {C} is attached to the instantaneous contact point between the sphere and the plane. The x-axis of coordinate frame {C} has the same orientation as the *internal unit* inside the spherical shell of the robot, leading to the fact that, in respect to coordinate frame {O}, coordinate frame {C}'s motion consists only of a linear motion along its x-axis and a rotational motion around the z-axis.

Since the only component of velocity in coordinate frame {C} is along the x-axis, the motion equations on the plane can be written as (1)–(3).

$$ {}^{O}x(t) = \int {}^{C}v_x(t) \cdot \cos(\alpha_1)\, dt \qquad (1) $$

$$ {}^{O}y(t) = \int {}^{C}v_x(t) \cdot \sin(\alpha_1)\, dt \qquad (2) $$

$$ \alpha_1 = \int \omega_C(t)\, dt \qquad (3) $$

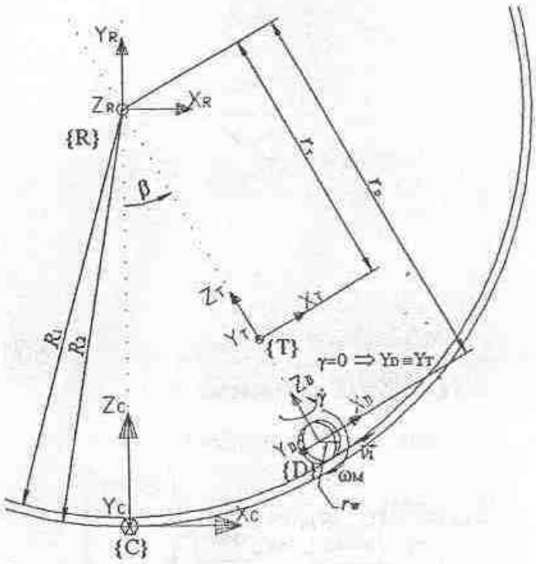

Fig. 4. Motion inside the spherical robot

3.1 Kinematical model

Inside the spherical robot consider the more general case of the *internal unit* being a single wheel. The particular case for the robot presented in this paper can be obtained considering this virtual wheel similar to the robot's wheels and resting in a spherical shell with internal radius equal to the radius of the circle described by the contact points between the *internal unit*'s wheels and the inner spherical surface of the real robot when it moves in a straight line. The virtual wheel has radius r_W and rotates with an angular velocity ω_M around the y-axis of coordinate frame {D}. This angular velocity ω_M translates into a linear velocity, v_1, for the contact point between the virtual wheel and the inner spherical surface. The virtual wheel also presents an angular velocity, $\dot{\gamma}$, around the z-axis of coordinate frame {D} in order to reorient the direction of motion.

As seen in figure 4, a coordinate frame {R} is attached to the centre of the sphere, another coordinate frame, {D}, is attached to the centre of the virtual wheel with the x-axis having the wheel's orientation and the y-axis perpendicular to the wheel, and an auxiliary coordinate frame {T} is defined as being attached to the mass centre of the robot.

In respect to coordinate frame {D}, the rotation speed of the wheel is given by (4).

$$ {}^{D}\omega_M = \left[0 \ \frac{v_1}{r_W} \ 0 \right]^T \qquad (4) $$

This rotation speed can be expressed in coordinate frame {R} as seen in (5), where $c\theta$ and $s\theta$ are shorthand for $\cos(\theta)$ and $\sin(\theta)$, being θ a general angle.

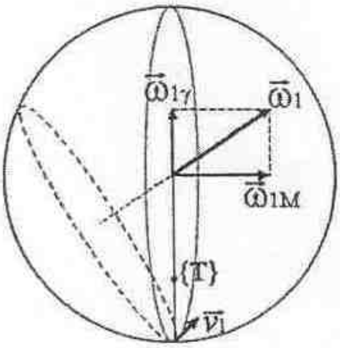

Fig. 5. Representation of *internal unit*'s angular velocity

$$ {}^{R}\omega_M = {}^{R}R_D \; {}^{D}\omega_M = -\frac{v_1}{r_W} \cdot \begin{bmatrix} c\beta \; s\gamma \\ s\beta \; s\gamma \\ c\gamma \end{bmatrix} \quad (5) $$

The angular velocity, ${}^{R}\omega_1$, of the virtual wheel, equivalent to the *internal unit*, with respect to coordinate frame {R} can be decoupled on two velocities ${}^{R}\omega_{1\,M}$ and ${}^{R}\omega_{1\,\gamma}$ resulting from velocities ω_M and $\dot{\gamma}$ of the virtual wheel, as illustrated in figure 5.

From (5) and considering the total radius inside the sphere $(r_D + r_W)$, the velocity component ${}^{R}\omega_{1\,M}$ can be given by (6) where it is seen its proportionality to ${}^{R}\omega_M$.

$$ \begin{aligned} {}^{R}\omega_{1\,M} &= \frac{r_W}{r_D + r_W} \cdot \left(-{}^{R}\omega_M\right) \\ &= \frac{v_1}{r_D + r_W} \cdot \begin{bmatrix} c\beta \; s\gamma \\ s\beta \; s\gamma \\ c\gamma \end{bmatrix} \end{aligned} \quad (6) $$

Component ${}^{R}\omega_{1\,\gamma}$ is given by (7).

$$ \begin{aligned} {}^{R}\omega_{1\,\gamma} &= {}^{R}R_T \; {}^{T}\dot{\gamma} = {}^{R}R_T \cdot \begin{bmatrix} 0 \\ 0 \\ \dot{\gamma} \end{bmatrix} \\ &= \begin{bmatrix} -\dot{\gamma}\; s\beta \\ \dot{\gamma}\; c\beta \\ 0 \end{bmatrix} \end{aligned} \quad (7) $$

Results (8) and (10), can be combined with (1)–(3) to give the global kinematical model of the spherical robot.

$$ {}^{C}v_x = \dot{\beta} \cdot R_2 \quad (8) $$

$$ \dot{\beta} = \left({}^{R}\omega_1\right)^T \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \frac{v_1 \cos(\gamma)}{r_D + r_W} \quad (9) $$

$$ \dot{\alpha}_1 = \left({}^{R}\omega_1\right)^T \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} $$

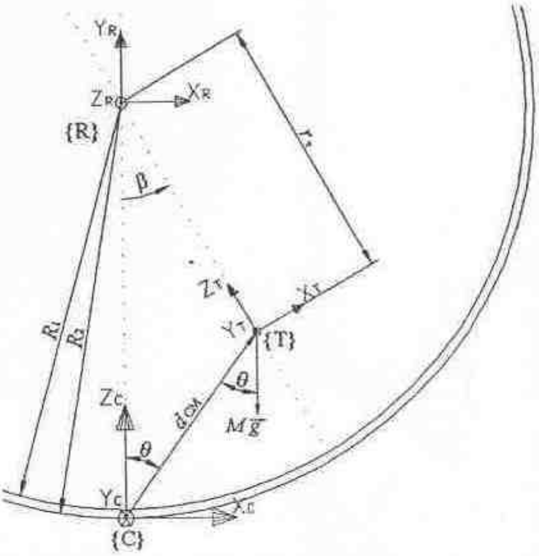

Fig. 6. Effect of moving the *internal unit*

$$ = \frac{v_1 \sin(\beta) \sin(\gamma)}{r_D + r_W} + \dot{\gamma} \cos(\beta) \quad (10) $$

3.2 Dynamic model

The robot will not respond instantly to velocity commands since it has its own inertia. The dynamical model is necessary to model the robot's behaviour and have a good knowledge of its motion properties.

Figure 6 illustrates the effect on the robot caused by moving the *internal unit*. When the *internal unit* moves, the robot's mass centre moves accordingly causing the entire robot to rotate in order to restore its equilibrium.

The unbalanced mass centre translates into a torque given by expression (11).

$$ \boldsymbol{\tau} = \boldsymbol{d_{CM}} \times \boldsymbol{M\,g} \quad (11) $$

This torque causes an angular acceleration as given by expression (12).

$$ \tau = I\,\alpha \quad (12) $$

Combining (11) and (12), the angular acceleration α can be expressed as a function of θ as seen in expression (13).

$$ d_{CM}\, M\, g \sin(\theta) = I\,\alpha \quad (13) $$

Since θ and β are related by expression (14) and angle β is easier to obtain from sensory data, expression (13) is rewritten in (15) as a function of β instead of θ.

$$ \frac{r_T}{\sin(\theta)} = \frac{d_{CM}}{\sin(\beta)} \Leftrightarrow \sin(\theta) = \frac{\sin(\beta) \cdot r_T}{d_{CM}} \quad (14) $$

$$r_T\, M\, g\, \sin(\beta) = I\, \alpha \tag{15}$$

The linear acceleration of the spherical robot can be easily determined since it is related to its angular acceleration through expression (16).

$$a = \alpha\, R_2 \tag{16}$$

It is then possible to express the linear acceleration of the spherical robot as a function of β, as expressed in (17).

$$a = \frac{r_T\, M\, g\, \sin(\beta)}{I} R_2 \tag{17}$$

The acceleration of the spherical robot characterises its motion dynamics. It should be noticed that the robot's moment of inertia, I, is not a constant in this case since the mass distribution of the robot around the contact point, changes with the rotation around that point. As a consequence, the moment of inertia is itself a variable depending on β.

4. THE ROBOT'S CONSTRUCTION

In order to operate the robot and perform its control, a set of equipment is necessary.

The actuators of the *internal unit* are radio-control servos (R/C servos) modified for continuous rotation. This solution was adopted since they have high torque for their size, and are easily available.

For the motion control it was adopted inertial sensing as feedback. The feedback was implemented in the robot by a basic navigation unit consisting of a 3-axis accelerometer and a 3-axis rate gyro. The gyros give heading information that is combined with the accelerometers data to determine the robot's acceleration, velocity and position relative to an inertial frame attached to a fixed point on the ground.

All of the control implemented in the robot was done in digital programmable logic devices (PLDs). Since the sensors used had analog outputs, their interface with the PLDs was done through an analog-to-digital converter.

As a way of simplifying the hardware in the robot, the motion control algorithms were implemented remotely on a computer, being the communication between robot and computer done recurring to radio-frequency transmitters and receivers.

5. ROBOT'S CONTROL HARDWARE

As mentioned above, the control algorithms were implemented in a remote computer, with communication being done through radio frequency transmitters and receivers. In order to achieve full-duplex, high-speed communication, it was used a transmitter-receiver pair for communication in one direction, and another pair for communication in the other direction. Figure 7 illustrates the interface between computer and robot.

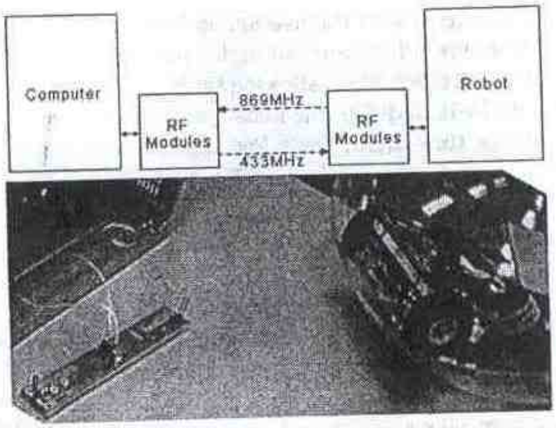

Fig. 7. Interface between computer and robot

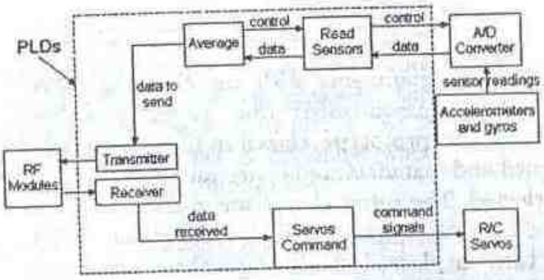

Fig. 8. Robot's architecture

On the robot's side, all hardware interface and control was achieved using only PLDs. This decision provides true parallelism in the execution of the several tasks, and allows high integration of circuits. A block diagram of the robot's architecture is illustrated in figure 8.

The "Transmitter" and "Receiver" circuits interact with the radio-frequency (RF) modules, respectively sending and receiving the bits which the RF modules modulate/demodulate to/from the RF spectrum. The data received by the robot are the desired speeds for each of the *internal unit*'s wheels. The circuit "Servos Command" converts these desired speeds into command signals for controlling the rotation speed of the servos.

Circuit "Read sensors" interacts with an 8-channel analog-to-digital converter using the SPI interface protocol as described in its datasheet (Maxim MAX186, 1996). The accelerometers and gyros outputs are connected to different ADC channels and "Read Sensors" circuit sequentially and continuously instructs the ADC to convert them all, feeding them back to circuit "Average". This circuit averages the sensors data during a certain period, after which the average is transmitted to the computer. This way, an high sampling rate of the sensors is achieved, allowing for high frequency data to be included in the measurements, while at the same time allows for a low transmission rate to be used from the robot to the computer.

On the computer side, a data acquisition board is used to interface with the RF modules, and an interrupt service routine provides the interface between the control application and the data acquisition board. The rate at which the computer can serve the interrupt routine limits the transmission rate to a mere 1.67 KHz, which is more than sufficient for a control rate of 10 Hz.

6. EXPERIMENTS AND RESULTS

The first experiments with the spherical robot prototype demonstrated that it works as expected. The prototype, shown in figure 1, was designed and manufactured by us, and still has to be perfected. The *internal unit* was made to operate as differential drive to give the robot the ability to turn in place, but although the construction with the four wheels is appropriate for driving in a straight line, when it comes to turning, there is the need for a lot of slipping for the *internal unit* to turn inside the spherical shell.

At the moment it is not yet implemented the closed loop control of the robot, instead it is directly teleoperated from the computer's keyboard. This control is the future step of the system. Actual experiments show that the robot's motion seems very rough when it is driven manually, mostly because the commands are not continuous. When the *internal unit* tries to turn, there are great accelerations and instability, as sensed by the inertial sensing unit.

The experiments show that the robot can be driven easily in a straight line and has problems to turn when operated manually. The turning problem can be partially solved by a closed loop automatic control that uses the feedback from the rate gyros to obtain the real turning of the robot.

One of the weakest properties of this particular robot's surface is obstacle crossing at very low speeds, since the robot turns away from the obstacle as a result of the low friction between the robot and the ground due to their single contact point. Another result of this low friction is the fact that when turning, it is not only the *internal unit* that turns inside the spherical shell, but often the entire robot also turns in the opposite direction. This is another reason to study algorithms for closed loop control using the feedback from the gyros to determine the real angle turned by the robot.

7. CONCLUSIONS AND FUTURE WORK

A spherical mobile robot was designed and constructed. Its motion properties were analysed and verified by a set of experiments. The control of the robot's devices was built using mainly digital programmable logic devices, which proved to be a very suitable solution for interconnection of devices achieving high integration of circuits in a mobile robot such as this.

There were identified some restrictions in the designed *internal unit*, but some can be overcome by an automatic control that takes into account these weaknesses. The first step into the future is the realisation of this automatic control. It's also desired to improve the performance of the robot in bumpy terrain and to integrate in the robot some capabilities to make it more autonomous since the actual dependence on an external computer for control is not very attractive for many applications.

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