Improvements on an autonomous robot prototype

APERFEIÇOAMENTOS EM UM PROTÓTIPO DE ROBÔ AUTÔNOMO

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ABSTRACT

Autonomous robots may be understood as vehicles carrying electronic devices and sensors in order to be capable of receiving instructions from a central unit, processing them and performing the desired task, although intermittently supervised and updated by the central unit. This concept is applied to the present work, where a two-wheeled mobile robot executes trajectories composed of specified arcs of circumferences monitored only by the angular displacement of the motors, permitting closed loop control of these. Based on rigid body mechanics, it was possible to describe the motion of the vehicle in terms of the angular displacement of the motors. Although a tracking problem, the parameters of the controllers of the two motors were determined considering the problem as a step input regulation one. Improvements introduced on a previous simpler version of the autonomous robot are described. These improvements consisted of adding to the vehicle's control software the capacity to follow a generalized trajectory, composed of a succession of fixed simple trajectories. For this purpose it was necessary to alter the software structure. The parameters for all successive trajectories are transmitted from a computer to the vehicle. Future improvements are possible, such as including a radio link to allow on-line trajectory updating and including environmental sensors to aid vehicle guidance.

KEYWORDS

Autonomous robot. Trajectories. Closed loop control.

RESUMO

Robôs autônomos podem ser entendidos como veículos equipados com dispositivos e sensores eletrônicos, de forma a serem capazes de receber instruções de uma unidade central, processá-las e desempenhar uma tarefa desejada, embora intermitentemente supervisionados e atualizados pela unidade central. Essa concepção é aplicada ao presente trabalho, onde um robô móvel dotado de duas rodas executa trajetórias compostas de arcos específicos de circunferência ajustados apenas pelo desvio angular entre os motores, permitindo o controle de malha fechada destes. Baseando-se na mecânica dos corpos rígidos, é possível descrever o movimento do veículo em termos do desvio angular entre os motores. Aperfeiçoamentos introduzidos na versão anterior (mais simples) do robô autônomo são descritas. Esses aperfeiçoamentos consistiram em adicionar ao software de controle do veículo a capacidade de efetuar uma trajetória geral, composta por uma sucessão de trajetórias simples fixas. Para esse propósito, foi necessário alterar a estrutura de software. Os parâmetros para todas as sucessivas trajetórias são transmitidas de um computador para o veículo. Futuros aperfeiçoamentos são possíveis, como a inclusão de um enlace-rádio para permitir atualizações de trajetória em tempo real e a inclusão de sensores para guiar o veículo em diversos meios.

PALAVRAS CHAVE

Robô Autônomo. Trajetórias. Controle de Malha Fechada.

INTRODUCTION

The present work describes improvements introduced on a previous version of an autonomous robot in order to make it capable of following a generalized trajectory. A mechanical analysis of the robot behavior is also summarized.

The autonomous robot is a small unmanned two-wheel vehicle that uses a DC motor with reduction gear to drive each wheel, with independent control of each motor and some processing capability in order to transform instructions into the corresponding movement. Each wheel control is exerted in closed loop by a separate dedicated microcontroller, with the aid of optical sensors and encoders to determine each wheel's angle. These two microcontrollers are driven by a main microcontroller, which does the processing needed to control the robot trajectory. Parameters to determine the trajectory are transmitted to the robot from a computer.

The previous version of the robot was capable of following a trajectory composed of a single arc of circumference. It was also possible to follow a straight segment as a particular case of arc, as was turning around without a translational movement. Parameters transmitted from the computer to the robot included arc radius, acceleration and distance to be covered.

The introduced improvements consisted of adding to the robot the capability of following a generalized trajectory composed of a number of arcs of circumference without the need to interrupt the movement. Again, a straight segment is a particular case of circumference, as is turning around the vertical axis that passes through the mid point between the wheels, without translation; this latter maneuver is useful for changes of trajectory orientation and to circumvent obstacles that impose a sharp angle to the trajectory. The parameters to be transmitted from the computer to the robot consist of a number of collections of the parameters needed for each arc of circumference, which are radius, acceleration, speed and distance. The number of independent arcs is limited only by the memory available size.

The addition of the capability to follow a sequence of several independent elementary trajectories was performed by modifying the software that controls the main microcontroller in the robot. In order to make this modification possible, it was necessary to alter the program structure. A modification of the software executed in the computer was also necessary, both to accommodate the transmission of a number of collections of parameters and to make the user interface more user-friendly.

A trajectory composed of a succession of arcs of circumferences may be considered, for the purposes of this work, a generalized trajectory since it is possible to decompose any trajectory (even if analytically not composed of arcs of circumferences) in small sections that can be approximated by such arcs.

The transmission of parameters from computer to the vehicle is performed before the start of the movement by a flexible cable, which may be disconnected after the transmission, to allow the robot completely free movement. After transmission, a command to start movement is given to the robot.

A single prototype of the previous version has been constructed, modified to include the improvements, and successfully tested; however, any number of such unmanned vehicles could be controlled by a single computer. A small change in the control software in the computer and in the robot would be needed to allow the transmission of different trajectories to the robots, since each transmission would have to include an address to identify each robot.

We may consider associated to this work the concept of distributed intelligence, since a central decision-making computer specifies trajectories and gives instructions to the processors of one or more vehicles, which command the motors and receive sensor information so as to follow the instructions autonomously.

The motivation for the previous version was the robot football tournaments (FIRA, 1996). In these events, the vehicles have two wheels driven by servomotors and are capable, basically, of movingforward, backwards and turning around, with the control loop closed by an external camera, connected to the central computer. The motivation for the present work was to increase the number of degrees of freedom of the robot. Considering this motivation and even going beyond it, the approach may be later extended to include other capabilities.

The vehicle is sustained and propelled by two wheels.

The third point needed to maintain it in an upright position is a simple fixed support. Being a two-wheeled vehicle, with a dedicated microcontroller for each wheel and one main microcontroller, the robot includes two local closed loop controls, using the encoders mounted on the axes of the motors and emulating PID compensators. This assemblage may lead to progressive error due to the slippage of wheels and pulleys and to imprecision in the mechanical construction of the robot. The verification and updating of the trajectory by a central unit, having more accurate sensors, would, therefore, be convenient, but has not been included in the present version. It should also be noted that due to slippage and other factors, the vehicle may present a non-linear behavior. Future improvements, either by the inclusion of a camera connected to the computer or of sensors to make possible the orientation with respect to obstacles and other characteristics of the environment may allow the implementation of an overall closed loop control to correct such cumulative errors.

Analysis of the problem, software development and testing were the object of a Dissertation, valid as a Final Project for the Telecommunications Engineering Course at Universidade Federal Fluminense, Niterói, Brasil (Barbosa, 2004). The initial version of the vehicle was fully developed as a research work for an M.Sc. Thesis, also at this University (HONDA, 2002).

In the following sections, aspects of the mechanical modeling, controller design, a summary description of the robot's previous version, modifications made, results obtained and suggestions for future development are presented.

MECHANICAL MODELING OF THE VEHICLE

In a previous work (NORONHA at al., 2003), a thorough description of the modeling that can be applied to this vehicle was described. The present analysis is based on that work.

ANALYSIS

It may be shown that the following equations allow for the modeling of each DC motor-gearbox-wheel system:

$$L.\dot{i} + R.i + K.\dot{\varphi}_M = V \qquad (1)$$

$$J_{eq}.\ddot{\varphi}_M + f_{eq}.\dot{\varphi}_M - N.K.i = -T \qquad (2)$$

Where *V, i, L R* and K are, respectively, the applied electric tension, the current on motor armature, its inductance and resistance and the DC motor constant, while T, φ_M , J_{eq}, f_{eq}, and N represent the reaction torque of floor on wheel, the motor angular displacement, the equivalent moment of inertia and rotational damping coefficient, referred to the motor, and the gearbox reduction ratio. The reaction torques of the driving wheels, T_e for the external wheel and T_i for the internal one, are, by its turn, function of the dynamics of the vehicle, i.e., they depend on the inertia and on the movement of the vehicle, as described in the following.

Assuming the vehicle as a rigid body, its movement may be decomposed into the translational movement of its center of mass, CM, and the rotational movement of the body around the CM, both movements caused by the external forces that act on the vehicle. Limiting the analysis to horizontal plane movement, these forces may be considered to be only the friction forces of the contact of the wheels on the floor. Considering initially the translational movement, this is characterized by the two scalar components of the CM acceleration, one tangential to and the second normal to the trajectory, at and an. Measuring the vehicle movement from an inertial frame of reference and taking into account the free body diagram of Fig. 1, Newton's Second Law requires, for the direction tangential to the trajectory, that:

$$F_{et} + F_{it} = m.a_t \qquad (3)$$

These force components, F_{et} and F_{it} are the reaction of the floor on the wheels due to their driving action and *m* the vehicle mass. Hence, the CM translational movement takes place according to:

$$T_e + T_i = r.(F_{et} + F_{it}) = r.m.a_t \qquad (4)$$

Where *r* represents the wheel radius. An equivalent analysis may be performed in relation to the rotational movement of the vehicle. Assuming that the plane, normal to the trajectory and containing the CM, also contains the contact points of the wheels with the floor, then the normal to the trajectory components of the contact forces do not produce any torque in relation to the CM. This, in turn, leads to the following equation of force moments relative to the CM:

$$F_{et}.b - F_{it}.b = I.\ddot{\theta} \qquad (5)$$

Where *b* stands for the vehicle half width, I the moment of inertia of the vehicle relative to a vertical axis passing through the CM and the vehicle angular acceleration. Hence, similar to Eq. (4), it may be established that:

$$T_e - T_i = r.(F_{et} - F_{it}) = r.I\ddot{\theta}/b \quad (6)$$

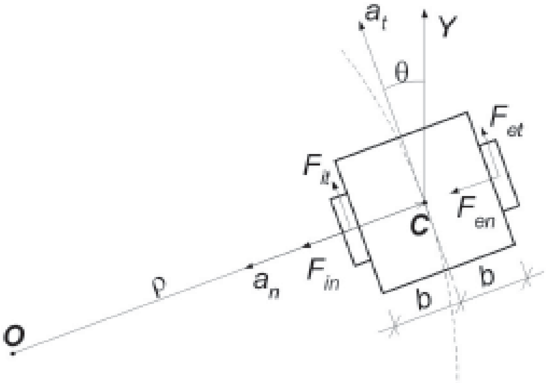


Figure 1. Free body diagram of the vehicle

Taking into account that at is equal to $\ddot{\theta}$ times *p*, the radius of curvature of the CM trajectory, then, for the back torque T_e of the external wheel, Eqs. (4) and (6) lead to:

$$T_e = \ddot{\theta}.r.(m.\rho + I/b)/2 \quad (7)$$

On the other hand, while there is no wheel sliding, the movement of the vehicle is related to the rotational movement of the two motors through the linear velocity of the center of the wheels. That is, as the contact points of the wheels with the floor have no velocity, the following is true:

$$v_{We} = (\rho + b).\dot{\theta} = r.\dot{\varphi}_{We} = r.\dot{\varphi}_{Me}/N \quad (8)$$

Where $v_{We}, \dot{\varphi}_{We}$ and $\dot{\varphi}_{Me}$ are the linear velocity of the center of the external wheel, its angular velocity and the angular velocity of the associated motor. Through this equation, a relation between the angular velocities of the vehicle, $\ddot{\theta}$, and of one motor, $\dot{\varphi}_{Me}$ is established. Differentiating it in relation to time and substituting into Eq. (7) leads to the following expression for the back torque T_e and the angular acceleration of this motor:

$$T_e = \ddot{\varphi}_{Me}.r^2.(m.\rho + I/b)/(2N.(\rho + b)) \quad (9)$$

Hence, after substituting this relation for the back torque of the external wheel into Eq. (2), the differential equation that describes the mechanical behavior of the external motor/wheel set is given by:

$$J_{ef}.\ddot{\varphi}_M + f_{eq}.\dot{\varphi}_M - N.K.i = 0 \quad (10)$$

where:

$$J_{ef} = J_{eq} + r^2.(m.\rho + I/b)/(2N.(\rho + b)) \quad (11)$$

Equations (10) and (11) are also applied to the motor/wheel set internal to the curve by using a negative value of *p*. In this way, a high value of *p*, in modulus, implies that the trajectory of the vehicle is almost straight, while a small value provides a curvilinear movement, with center of curvature at the same side of the wheel for negative *p*, or the opposite side for positive *p*. For *p* equal to 0, the vehicle is turning around itself, with indeterminate sense, while at *p* equal to *-b* there is a singularity, but, for this value of *p*, the motor should halt while the vehicle would be turning around the vertical axis passing through the contact point of the wheel, belonging to this motor, with the floor.

It should be observed that the J_{ef} coefficient is made of two terms. The first represents the rotational inertia of the motor/wheel set and the second the inertias of translational and rotational movements of the vehicle. Because it introduces these effects into the equation of movement of the motor, this second term depends on the trajectory of the vehicle, which may cause a non-linear behavior on the dynamics of the vehicle. However, this dependence is only in relation to the radius of curvature and, if the masses on the vehicle are distributed in such a way as to approximate the radius of gyration, $k = (I/m)^{1/2}$, to the half width b, this dependence is drastically reduced. If this is achieved, the problem becomes linear and it is possible to determine one unique set of control parameters for any specified trajectory.

As discussed in the Introduction, the specified trajectory of the vehicle is supposed to be limited to one or more arcs of circumference. Also, as discussed above, in the following is taken into account only the external motor/wheel set. Let *S*, p_d and a_o respectively be the length, the radius and the constant CM scalar acceleration of a specified arc of circumference. Let also s_o and φ_{Mo} be the values of the CM speed and of the motor shaft angular position in the beginning of the arc. Substituting the specified trajectory parameters into the motor variables, it is possible to establish an expression for the specified external motor displacement:

$$\varphi_{Md} = \varphi_{Mo} + \dot{\varphi}_{Mo}.t + (\ddot{\varphi}_{Md}.t^2)/2 \tag{12}$$

where:

$$\dot{\varphi}_{Mo} = s_o.N.(\rho_d + b)/\rho_d.r \tag{13}$$

For the internal motor, a similar expression is obtained. It is now possible to determine the tracking errors of the motors through the differences between φ_M and φ_{Md}.

CONTROLLER DESIGN

The mass of the vehicle was measured on a digital balance with a sensibility of 0.01 kg while the moment of inertia of the vehicle, I, was experimentally determined in accordance with a methodology proposed by Inman (1994), obtaining:

m = 1.64 kg and I = 1.85x10-2 kg.m2

The other parameters, used on the controller design and simulation and also on programming the vehicle, were:

$r = 17.5\mathrm{x}10^{-3}$ m $b = 55\mathrm{x}10^{-3}$ m

$K = 10.9\mathrm{x}10^{-3}$ V.s/rad $J_M = 1.62\mathrm{x}10^{-6}$ kg.m^2

$R = 1.17\ \Omega$ $L = 0.58\mathrm{x}10^{-3}$ H $N = 6.3$

$J_R = 2.74\mathrm{x}10^{-6}$ kg.m^2 $f_M = 1.10\mathrm{x}10^{-4}$ N.m.s/rad

The motor parameters, *R, L, K,* J_M and f_M, were taken from the manufacturer catalogue (Pittman Motors, 2000) and J_R was calculated (Honda, 2002). For the controller design, J_{ef} was considered constant and equal to 5.05x10-5 kg.m^2.

The design of the controllers for the motors begins from the differential equations that describe each motor, Eqs. (1) and (10). From these, the transfer function, *Gp(s)*, between the angular displacement of the motor, φ_M, and the armature electric tension, *V*, is established:

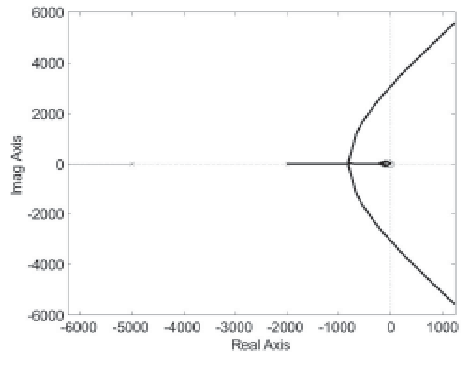
$$Gp(s) = \frac{N\,K}{s[J_{ef}\,L\,s^2 + (J_{ef}\,R + fL)s + fR + NK^2]}$$

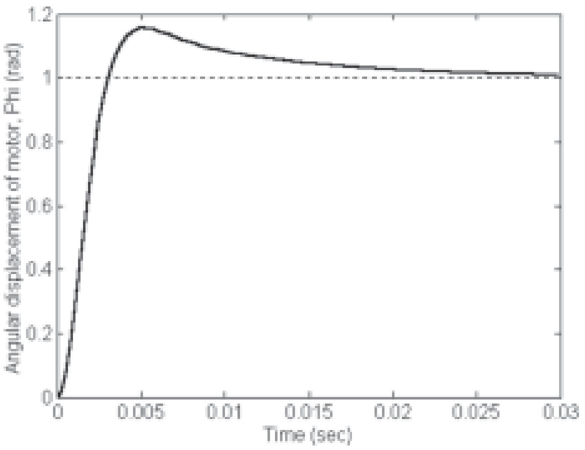
Substituting the numeric values of the parameters, three real poles are identified, one at -26.56, another at -2004, and the third pole at the origin. In order to maintain the tracking error null, a controller that furnishes a signal to correct the deviations caused by internal and/or external factors is desired. The easiness of implementation and the robustness of its performance make the PID controller an appropriate choice for this application. Furthermore, the classic design procedure through the root locus (Aström e Hägglund, 1988) may be directly employed. On the other side, if the trajectory does no change too rapidly in relation to the dynamics of the system (inertias, torques etc), this tracking problem may be analyzed as a regulation problem with step entries. The transfer function, H(s), of a PID controller may be expressed as:

$$H(s) = \frac{K_d s^2 + K_p s + K_i}{\varepsilon s^2 + s} = K_c \frac{(sT_1 + 1)(sT_2 + 1)}{\varepsilon s^2 + s} \tag{15}$$

Although arbitrary, after evaluating many simulations, T_1 and T_2 were respectively chosen to be 0.05 and 0.01. In this way, two zeros were placed at -20 and -100. The value of ε was fixed as 0.0002, in order to produce a left pole, far from the dominant poles of the plant. The chosen value for the *Kc* gain was 1000. The root locus of the closed loop control system and a step response of the system are presented at Figs. 2 left and right, respectively.

Figure 2. Left: Root Locus of the closed loop controller of one motor. Right: Step response of control system.





PROTOTYPE CHARACTERISTICS AND RESULTS

Besides the vehicle's mechanical modeling, the previous version development involved the specification of components and the assemblage and testing of the vehicle. Components included: motor and mechanical reduction, optical sensor with encoder, dedicated microcontrollers, main microcontroller, battery, vehicle body, wheels and auxiliary electronic and mechanical components.

The development also involved measurements of mass and moment of inertia, development of software for the dedicated microcontrollers, for the main microcontroller and for the computer, testing the vehicle, recording the results and measuring the values associated with the trajectories obtained.

As a main microcontroller, a Parallax Basic Stamp BS2sx model was used, with the following characteristics: 20 MHz Clock frequency; 2 kBytes EEPROM; 32 bytes RAM; Serial communication of 50 to 120 kBauds.

As dedicated microcontrollers, two National LM629N-6 were used; these microcontrollers are designed mainly for use to control servomotors and cannot be programmed independently. In fact, they must be "slaved" to the main microcontroller, which sends all commands that must be executed by the dedicated microcontrollers. The main microcontroller uses 8 I/O pins to send these commands, plus other 8 pins for other data in/out. Therefore, the improvements that were later added would have to deal with the main microcontroller software.

Batteries used: two 7 volts DC batteries .

Parameters transmission from computer to vehicle: serial, through cable with connectors leading from a db9 connector on the robot to the COM2 serial port of the computer. The parameters were passed immediately from the main microcontroller to the two dedicated microcontrollers. This solution implied the necessity to send new parameters every time a new trajectory was desired.

The vehicle has the following two modes of operation:

Mode velocity: accelerates (parameter SPA) until a preset speed is reached (parameter SPV); continues until a new set of parameters is introduced by cable.

Mode Position: accelerates (SPA) to specified speed (SPV); moves until specified distance has been reached (parameter SPP) and finally decelerates to full stop with the same absolute value of the initial acceleration.

For each set of parameters sent, a single trajectory was followed. Sending another set of parameters implied a pause in the vehicle's movement. Examples of the obtained trajectories are presented in Fig. 3 (Honda, 2002).

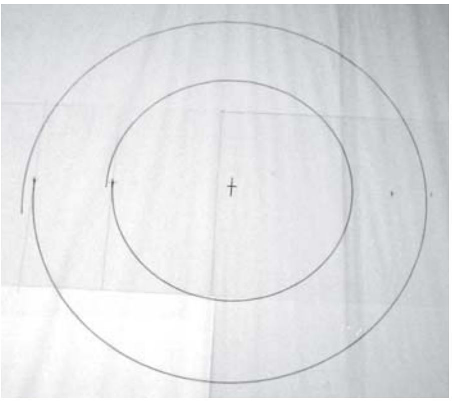


Figure 3. Experimental results of the previous version: Photo of two circular trajectories of 1.0 m and 0.6 m in diameter

ROBOT WITH GENERALIZED TRAJECTORIES

After the improvements, the robot became capable of supporting generalized trajectories. A generalized trajectory is a sequence of elementary trajectories. To initiate a generalized trajectory, all necessary parameters are transmitted to the vehicle initially. Once the vehicle starts to move, it follows the complete sequence without needing to stop or to send new parameters. The number of elementary trajectories that may compose a generalized trajectory is limited only by the available size of the memory.

To introduce these improvements, two programs were modified: the main microcontroller program and the communications program in the computer.

While in the previous version the parameters were sent immediately from the main microcontroller to each dedicated microcontroller, the modified software incorporated the data in itself, so that transmitting the program (which had to be done also in the previous version to begin operations) suffices to transmit the data. The data can, then, be composed of a succession of sets of parameters.

The structure of the program had to be modified to allow this different approach. There was no need to increase the size of the memory. The areas of the memory used, however, were different from those used in the previous version. Now, the parameters are passed to the lower addresses of the memory, where they are read by the program during its execution in the main microcontroller. The use of the memory's lower portion allows more storage space, which makes possible a large number of elementary trajectories to be informed to the vehicle and followed in succession.

The modification of the computer software took into account the fact that sending the data imbedded in the program simplified the actions necessary to send them. In the previous version, an interface written in Qbasic was used with the purpose to send the data; in the modified software, instead of the old interface, a new one, named "Montador", was developed. This new interface inserts the data into the program, in such a form that they can be separated during initial processing in the main microcontroller. Besides, Montador offers a user friendly interface, with fields and windows that can easily be filled up.

With the new program, it is possible to command the robot to follow elementary trajectories of the following types:

- Forward
- Backward
- Turn clockwise
- Turn counterclockwise
- Arc with a specified radius

These trajectories can be combined to form generalized trajectories.

EXPERIMENTAL RESULTS

A photograph of the robot, without its cover, is shown in Fig. 4 - a; it has the same aspect of the initial version, since it is exactly the same hardware.

The robot was tested and behaved as expected.

Several sessions of testing were performed, with different combinations of basic trajectories.

One of theses trajectories, given here as an example, was so composed:

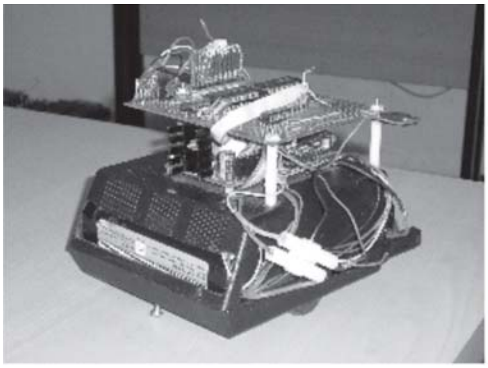
- straight line, acceleration 0,5 m/s^2, speed 1 m/s, distance 1,80 m;
- clockwise curve, acceleration 0,5 m/s^2, speed 1 m/s, total angle 90 degrees;
- straight line, acceleration 0,2 m/ s^2, speed 2 m/s, distance 0,60 m

A test bed was set up to record the combined trajectories. It consists of a large sheet of cardboard on a wooden board over which the robot was made to move. To record the trajectory, a pencil was fixed to the vehicle. This test bed is shown in Fig. 4 - b.

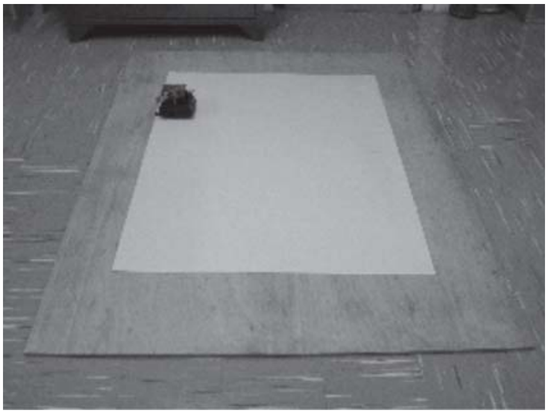
The result of a test performed on this test bed is presented in Fig. 5; this figure shows the actual trajectory, although, to photograph the trace left by the pencil, it was necessary to reinforce the trace by hand. This test was set up with a trajectory very different from the previously described, and was so composed:

- straight line, forward motion, distance 0,70 m;
- right turn without translational movement, 135 degrees;
- straight line, forward, distance 0,99 m;
- left turn without translation, 135 degrees;
- straight line, forward, distance 0,70 m;
- right turn without translation, 90 degrees;
- straight line, backward movement, distance 0,70 m.

Noting that 0,99 equals 0,7 m times the square root of 2, one sees that the trace shown in Fig. 5 corresponds to theses parameters. In the photograph, the vehicle has been located back in its point of departure.



a - Robot



b - Test-bed

Figure 4 - Robot and test-bed used to test it

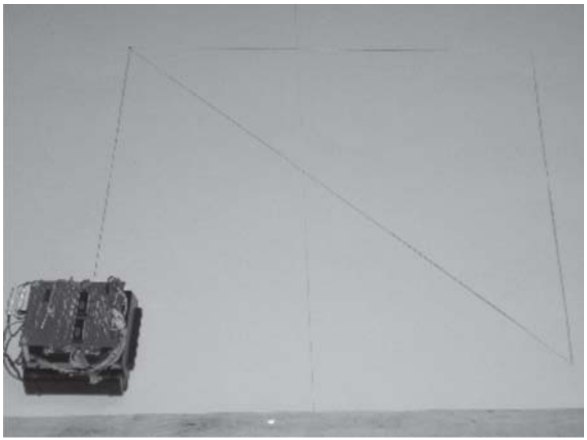


Figure 5 - Complete composed trajectory

FUTURE DEVELOPMENTS

With the same vehicle as a physical support and considering the possibility to update the electronics with more powerful microcontrollers, larger memory and improved auxiliary components, it is possible to develop new software, both for the microcontrollers and for the control computer, and add other devices, to improve the robot's performance.

The following improvements are being considered: to establish a VHF/UHF radio link between the computer and the vehicle, so as to allow parameters updating during the vehicle movement; to add environmental sensors to the robot to help in its orientation; to add a camera, connected to the computer, to observe the vehicle, so as to establish an overall closed loop to control the robot's position and movement; to increase the "intelligence" of the robot so that it will be capable of navigating from one specified point to another, amid specified obstacles; add more intelligence to allow the same navigation without specifying the obstacles (which, of course, assumes that a solution is possible without extreme measures, such as flying...).

CONCLUSION

Autonomous two-wheel vehicles with an electric DC motor driving each wheel can be controlled by microcontrollers that receive parameters for the vehicle's trajectory from a control computer. The vehicle, which had some processing capability that made it capable of following one elementary trajectory each time it received the parameters for this trajectory, had its software improved so that it is now capable of following a generalized trajectory, composed of a sequence of elementary trajectories. The vehicle was tested and behaved as expected. Several improvements to give the robot the capabilities for more complex behavior are possible and are being considered as future work.

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