DYNAMICAL BEHAVIOUR OF THE AUTONOMOUS MOBILE ROBOT "CAMÕES"

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ABSTRACT

This paper describes an Autonomous Mobile Robot project, developed by three senior students from the Industrial Electronics Engineering course during their probation period. A large robot was built in order to participate on the Festival International de Science et Technology 1998 *in Bourges, France. In this contest, besides other tasks, the robot was supposed to follow a track painted on the floor. A dynamical approach was used for that purpose and this paper refers to the trajectory control module responsible to keep the robot centered and properly oriented as it travels through the track.*

Keywords: Mobile Robotics, Autonomous Robotics, Dynamic Behaviour, Robot Contest.

INTRODUCTION

The project hereby described consisted of constructing an autonomous vehicle to participate in an international competition of mobile robotics, namely the "*Festival International des Sciences et Technologies*" held in France.

The main objective of the vehicle is to follow a track (line with constant width painted on the floor), whose colour is black or white contrasting with the chessboard type floor, where each square is two meters long painted in black or white colours. Besides following this track, it must perform some other tasks imposed by the competition rules, like to collect French billiard balls from the floor and select them according to its colour, to recuperate its path should the line become discontinuous. Although the main purpose of this project, was the participation in the referred competition, the techniques and methods implemented here have a potential application in industry, more specifically in the area of Automated Guided Vehicles (AGV's).

The construction of this robot, baptised with the name of "Camões", involved different areas of engineering such as Electronics, Computer Science, Control and Image Processing as well as Mechanics and, since the robot was built from scratch, it required also a great deal of handcraft. The project that was supposed to last six months, but due to the high involvement of the studentsit was built in just under three months.

Although a brief description of the robot is given in the next section, this paper refers only to the trajectory control module responsible to keep the robot centered and properly oriented as it travels through the track. The description of other modules of the robot can be found on related papers referred in the end of this text.

THE ROBOT

The robot "Camões" is built from a wood platform 1,2m long and 0,6m large, with two driving wheels located on the front end of the platform and a third free wheel mounted on the rear back for support of the whole structure.

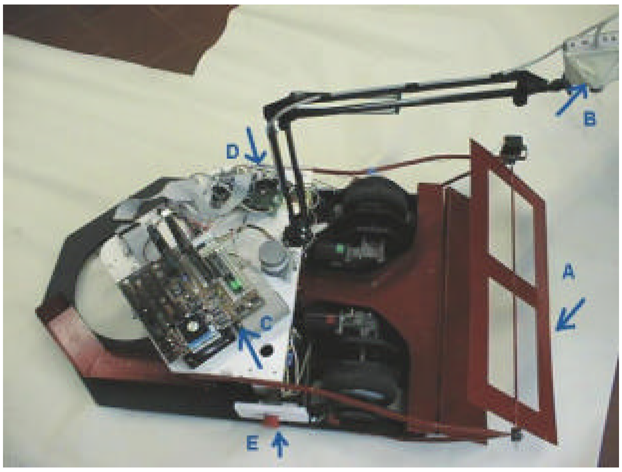
Two DC motors attached to the driving wheels run independently such that a heading direction can be defined by providing different velocity to the motors.

During the competition the robots were supposed to collect black and red billiard balls, store the red balls and reject the black ones. To implement this functionality a simple electronic and mechanical system was mounted over the platform.

In the trajectory control system a unique sensor (a colour CCD camera) provides all the feedback needed to close the control loop.

The brain of the whole system is a standard Personal Computer based on the iNTEL® Pentium ™ MMX 200Mhz microprocessor equipped with a conventional Video Captivator™ frame-grabber.

(a)



(b)

Fig. 1 – Photographs of the mobile robot "Camões", with decorative cover (a) and without the cover (b)

Legend:

A – Rotating shovels to collect the balls.
B – Color CCD video camera.
C – Computer.
D – Electronic board to interface the computer and the robot.
E – Emergency STOP button.

TRAJECTORY CONTROL

The purpose of the trajectory control module is to keep the longitudinal axe of the vehicle centred over the track and properly oriented according to the vector that is tangent to the trajectory, all the time. This means it is necessary to control simultaneous and independently two different variables:

- The angle Φ of the next track segment relatively to the robot's current heading direction.
- The offset Δ between the point of intersection of the track with the front of the robot and its central line

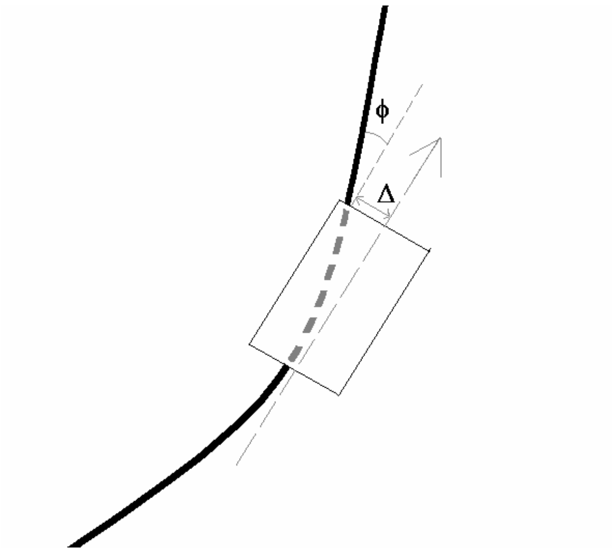


Fig. 2 – Description of the control variables

In order to keep the values of Φ and Δ close to zero, two independent controllers were implemented. The output of each of these controllers is an angular velocity W_Φ or W_Δ which is the W that would correct the error in the angle Φ and offset Δ, respectively. The final W demanded to the system is obtained from the mean angular velocity between the outputs W_Φ and W_Δ.

The trajectory control implemented in this robot has no resemblance with any of the classical proportional-integral (PI) or proportional-integral-derivative (PID) but instead, follows the approach from the Qualitative Theory of Dynamical Systems.

THE CONTROL ARCHITECTURE FOR CAMÕES

The control for Camões comprises two feedback loops. An inner loop corresponding to the proportional-integrative speed controller for each of the two motors an outer loop associated with the Qualitative trajectory controller. The architecture is represented in the next diagram.

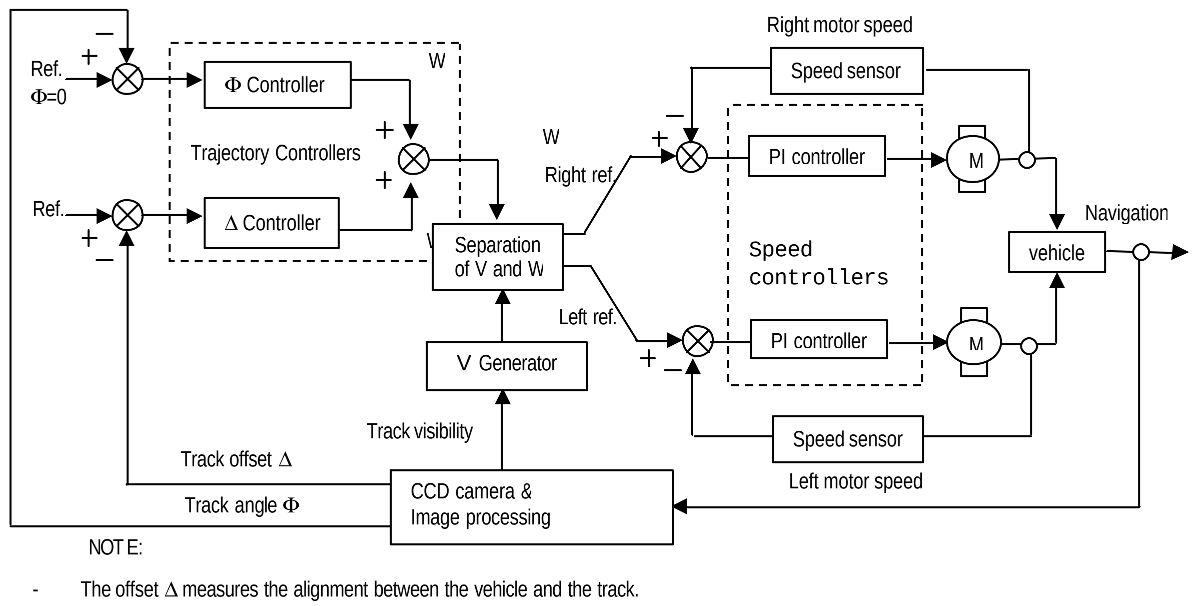


Fig. 3 – The robot control architecture

From the above diagram it can be seen that two levels of control hierarchy were implemented. The highest level, corresponding to the outer feedback loop, comprises the trajectory controllers that process the two trajectory parameters (Φ and Δ) outputted by the image processing subsystem. The second level in the control hierarchy provides independent velocity control for each motor. The control cycles are, obviously, much shorter in these inner control loops.

The global control loop output is an angular velocity *W*, which is obtained from the simple mean value between the outputs of the two trajectory controllers. The linear velocity *V* is calculated independently by the *V Generator* that produces a value of *V*, which is proportional to some measurement of track visibility, provided by the IP module, after some proper low-pass filtering. This *track visibility* coefficient is related to the number of intersecting bands detected [1]. Next, in the diagram, the values of *V* and *W* are converted in left and right motor speeds, which are the reference values for the velocity controllers. In the inner control loop the velocity sensor is an optical encoder hand-manufactured using old CD-ROM discs.

Qualitative Control

The aim of Qualitative Control is not to restrict pre-emptively the values of some system variables but to implement behaviours and decision-making in the higher levels of the control hierarchy.

In the specific case of the Camões robot, the trajectory Control determines which angular velocity the vehicle should assume, while the speed controllers make their best effort to force that velocity. It should be noticed that the lower levels of control hierarchy execute faster than the high level algorithms.

To implement a specific behaviour, the Dynamical programme searches for a differential equation (or system of equations) that have some qualitative properties which can be translated into the desired behaviour.

In its simplest form, the differential equation takes the form of:

$$\dot{x} = f(x)$$

A differential equation such as the one above, defines the rate of change of a variable (x) as time passes by and therefore the zeros of f(x) assume a critical importance because they represent the states of equilibrium for the system.

The zeros of f(x) are called *fixed points* to suggest the fact that once the systems reache one of these points it stays trapped and does not evolve unless it receives an external stimulus.

There are two types of fixed points (f.p.):

- stable f.p.
- unstable f.p.

A stable f.p. (attractor) represents a state of convergence to which the system will return, sooner or later, after being deviated by an external factor (stimulus). An unstable f.p. or repeller, corresponds to a singularity that the system will abandon to the slightest perturbation.

The following picture represents a system made of an iron ball suspend between two identical magnets and where two types of fixed points are easily identifiable in the three possible solutions for the system.

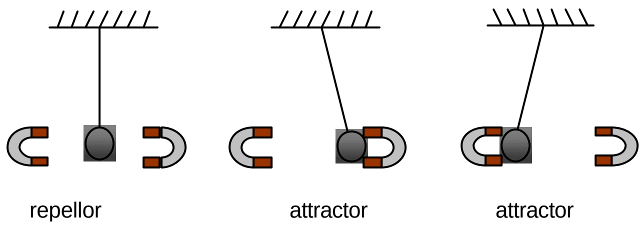


Fig. 4 – An example of a dynamical system with 3 equilibrium states (one stable and two unstable).

Another important aspect of f(x) is the time of relaxation (t) associated to each fixed point through the slope of f(x) in its neighbourhood. The value of (t) traduces the speed with which the system will converge to an attractor or diverge from a repeller.

Designing the Dynamics for Camões

Designing the Dynamics for Camões means constructing the differential equation f(x) mentioned previously.

The first step in such design consists in choosing the control variable. In this case the chosen variable was the angular velocity **W;** resulting in a 2^{nd} order differential equation (it should be noticed that **W= d**F **/dt**).

$$\dot{w} = f(w)$$

The next step consists of defining the behaviour the robot must assume. In the case of Camões the aimed behaviour keeps the values of angle F and offset D close to zero, within a limited range of angular velocity **W** and angular acceleration a .

This means that the system will produce a positive or negative value of **W** in order to zero the variable F or D**.**

All of the behavioural aspects being considered so far, can be modelled with a 2^{nd} order equation constructed from a 3^{rd} degree polynomial function represented in next picture.

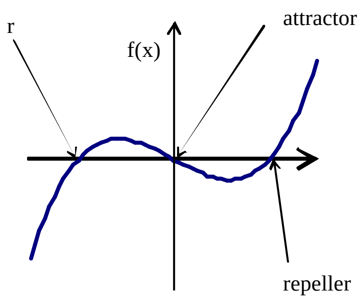


Fig. 5 – A 3^{rd} degree polynomial function representing a dynamical equation with one attractor and two repellers.

This equation has an attractor that will be used to drive the system into some value of **W** and also provides two repellers that can be placed in the maximum allowed values of angular velocity: $\mathbf{-W_{max}}$ and $\mathbf{+W_{max}}$**.**

Substituting the variable **x** with **W** and the function **f(x)** with **dW/dt,** the final dynamical equation obtained is given by:

$$\dot{w} = A(w - w_{max})(w - w_a)(w + w_{max})$$

where,

w_{max} - maximum allowed value for **W** (repeller)

w_a - current aimed value of **W** (attractor)

A - amplitude of the angular acceleration a (proportional to the relaxation time(t)).

The system will have two independent equation of this type running simultaneously, each one of them associated to the variable F or D**.**

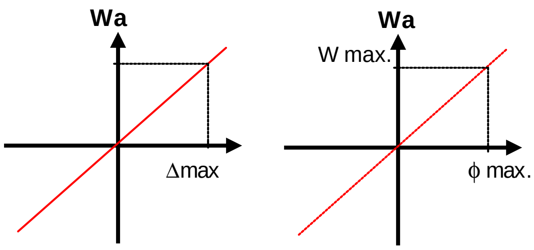


Fig. 6 – The position of the attractor *Wa* is proportional to *F* or *D*.

It is now necessary to define the 1st order part of the equation. That is, to relate the position of the attractors $\mathbf{W_a}$ as a function of F or D**.** For Camões, a linear relation was chosen although an exponential would make sense too.

The next graph shows the aspect of one of the two dynamical equations in three instants of time where its control variable assumes a positive, negative and null value, placing the attractor in Wa1, Wa2 and Wa3 respectively.

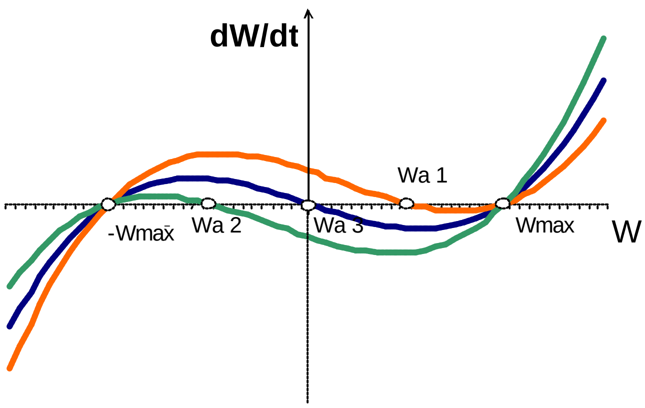


Fig. 7 – A snapshot of the system dynamics taken in 3 instants in time.

In each control cycle where the dynamical equation is recalculated, a value of angular acceleration is obtained. The resulting a must be integrated so that a more suitable variable such as the angular velocity (**W**) can be obtained. Since the control cycles are very fast, the angular velocity can be obtained from a through linear Euler's integration:

$$W' = \alpha.\Delta t + W$$

where:

a **-** angular acceleration obtained from the dynamical equation ($a = \dot{w}$)

D**t** - Euler's time / cycle time

W - actual value of angular velocity

W' - next value of angular velocity

Finally the two values of **W:** $\mathbf{W}_F$ and $\mathbf{W}_D$ should be conciliated so that a final value of **W** can be demanded from the motors. This conciliation consists in a simple mean of the two values.

The dynamic of Camões can be tuned solely through the parameter **A** of each equation which translates itself in the reaction time (or acceleration) of the vehicle.

Conclusions

For participating in a contest like the one for which this vehicle was built, a traditional heuristic approach could be used resulting in either better or worse results. But in this project the decision was taken to take a different approach. A dynamical behaviour was desired to produce not only random results as well as a different technique from the other teams.

The trajectory control, using this 2nd order dynamical equation was initially tested in a simulator where it proved to work quit remarkably. In the field, the results where somewhat compromised by the poor performance achieved with the speed controllers, but even so it has provided very satisfactory results allowing the vehicle to achieve speeds of 0,6 m/s in a track with curves of about 1m radius.

The utilisation of 2nd order dynamics produced some negative side-effects such as resonance manifested in a crescent oscillation of the vehicle direction in long and straight trajectories.

Even so, the implementation of the control architecture described in the diagram of fig. 3 proved to be an example of successful interfacing between control modules operating in different levels of abstraction. The application of Qualitative Dynamics to implement the higher levels of control also revealed itself as a potential alternative to Classic Control or some kind of Heuristic approach.

In this mobile robot a vision system made up of a colour video camera and a frame grabber is used to extract the values, to set up the dynamical system variables. Other sensors could be used but this way with only one camera more details can be read from the environment. And instead of using several sensors (one for each thing to be detected) only one is used.

ACKNOWLEDGEMENTS

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