Challenges and Solutions in an Autonomous Driving Mobile Robot Competition

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Abstract.

Mobile Robot competitions are an important way for dissemination of science and engineering to the general public but are also excellent way of testing and comparing different research strategies. In this paper we discuss how today's research challenges of Intelligent and Autonomous Mobile Robots are being handled by the Autonomous Driving competition that takes place in the Portuguese Robotics Open annual mobile robotics competition.

I. INTRODUCTION

A. Mobile Robot Competitions

One of the most critical challenges when organizing a mobile robot competition is the balance between science and entertainment. Media attention is very sensible to the entertainment value and media attracts the citizens for events that promote science and technology, as well as sponsors. Some competitions are purely media-oriented, such as some remotely operated robot contests regularly held on televisions. The disadvantage of pure entertaining competitions is the marginalization of the technical contribution [Osuka 2002].

Other competitions are more science-oriented, involving much more research relevance [Bräunl 1999].

Robocup [Kitano 1998], requires intelligent autonomous robots without neglecting the entertainment value by the association of robots to soccer.

Many science associations or governmental agencies promote annual editions of robotic contests like the AAAI Mobile Robot Competition [Michaud 2001], [Elinas 2002], the Association of Unmanned Vehicle Systems, Braünl 1998], [Manseur 2000], or DARPA which promotes the Darpa Grand Challenge (DGC) giving a 2 million dollar award to the winner (if any) of a 175 miles desert road race from Los Angeles to Las Vegas including dirty roads, trails, open desert and man-made obstacles [Murray 2005]. The price for the 2005 edition was awarded for the first time as five autonomous robots finished the race.

Many universities run their own local competitions as part of their educational activities [Rieber 2004], [Almeida 2000]. Others use standard available entertainment platforms like Lego Mindstorms and their RCX controllers. For instance, the Department of Mechanical Engineering at the University of Stuttgart uses LEGO robots to illustrate feedback control problems with competitions based in path following or active suspension control problems [Rieber 2004].

With or without competitions, the fact is that the use of robots (mobile or not) on education and research is increasing and many institutions already use them for education and research purposes [Schilling 2002], [Bruder 2003], [Lima 1998], [Weinberg 2003], [Ceccarelli 2003].

B. Portuguese Robotics Open Autonomous Driving Competition

This paper focus on a Mobile Robot competition held in Portugal since 2001, originally conceived for the 1st Portuguese Robotics Open, under the name of "Autonomous Driving". The goal was to set up a competition with a good balance between the entertainment value and the technical contribution of the work.

Current research challenges on Intelligent Autonomous Robots include:

- navigation, including self-localization, trajectory tracking (simplified when there is a real trajectory, e.g., a line painted on the floor), wheel speed control and obstacle avoidance;
- task planning and coordination;
- object recognition, sensor integration and world map building;
- learning and adaptation:
- cooperation between robots and robots and humans.

Cooperation (including with humans) is currently being efficiently handled by the several Leagues of Robocup [Kitano 2000]. Moreover, some impressive works have been carried out to deal with human/robot interaction [Macdorman 2004], [Minato 2004].

The Autonomous Driving Competition focus on single-robot problems, especially those concerning navigation, trajectory tracking, task coordination and object recognition. The Autonomous Driving Competition rules reflect the research topics the rules committee wants to see developed every year when it updates the rules. Their current version is detailed in the next section.

II. AUTONOMOUS DRIVING COMPETITION RULES

The Autonomous Driving competition aims at promoting developments in devices, techniques and systems usable for vehicle autonomous driving either in restricted areas or, hopefully in the future, larger public spaces, such as pathways, roads and parks. Therefore, the challenge comprises a path with an 8-shaped configuration simulating a road, which, for the last version of the competition, defines a two-way street about 1.5 m wide (Fig. 1). Apart from the scale factor, the challenges associated to this competition reflect as much as possible real situations.

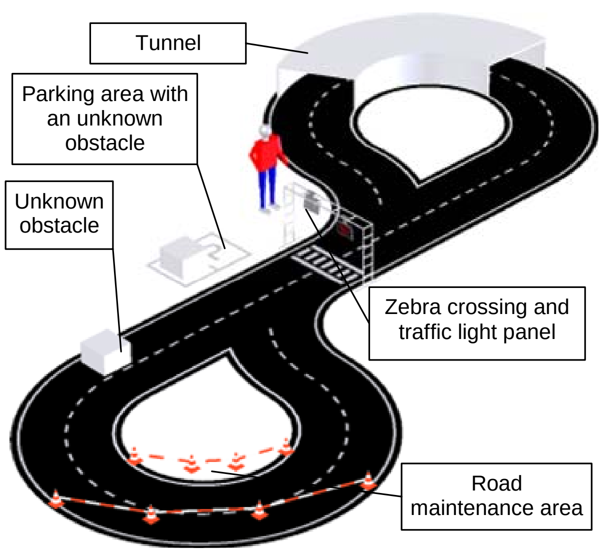

Fig. 1 – Autonomous Driving competition area.

The competition develops in 3 phases with increasing complexity, since new elements add up successively after each phase. The first phase demands simple motion along the path and the accomplishment of 2 complete laps, plus stopping at the zebra crossing. Phase 2 includes a panel with light indications for the robot to obey (Fig. 2); indications may point the way to follow (go ahead or turn at the crossing), give an order to stop or, finally, to proceed to a parking area located off the road. This park has two places from which one is already taken by an unknown obstacle.

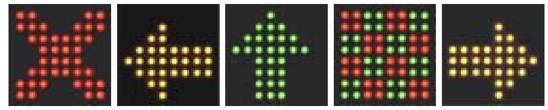

Fig. 2 - Signs available at the traffic light panel

Also in phase 2, a white box is placed on the road occupying one of the lanes, forcing the vehicle to take the other lane making the appropriate deviations without getting off the road; the box location is unknown beforehand. The third and last phase includes a tunnel; this obstacle affects light conditions as well as the road borders. A final difficulty appears also in phase 3; part of the road is replaced by stripes and cones signalling an area of road maintenance. The original path is replaced by a guided corridor and the robot must comply with this newly shaped route. The design of this section is also unknown beforehand.

Robot performance is assessed by its average velocity, but also by the penalties for not respecting signs or by colliding against objects in the competition area.

III. COMPETING ROBOTS

After several years of competition, some robots have evolved, others were completely rebuilt. In the next sections we present some representative robots competing in this class and how they were specifically tackled to handle the research issues.

The development of these robots involved many developments on areas like, for instance, sensor fusion (Made in Águeda), image processing, structure modeling (ATLAS), distributed systems development and integration (DET-UA) and discrete event systems (IQ).

A. Made in Agueda

The “Made in Agueda 2005” robot was developed in a Polytechnic School (Escola Superior de Tecnologia e Gestão de Águeda - University of Aveiro - Portugal, www.estga.ua.pt) and come out as a natural evolution of a small-sized robot built for a robot contest called Micro-Rato (an annual robot contest that takes place in the University of Aveiro since 1995, http://microrato.ua.pt/).

This challenging project resulted from the interest of a small team in applying electromechanic engineering concepts to the total development of a practical device. Moreover, for everybody involved, this was an extra-curricular activity in an entirely new research area, as the School had no tradition on Robotics.

The premises behind this project were: to work under a very limited budget, to fully obey to the contest regulation and, simultaneously, to develop a robot with a better performance than all its competitors. To accomplish this, it was necessary to use appropriate vision devices in the robot.

In the present state of technology, common microcontrollers are not powerful enough to the image acquisition and processing tasks, therefore the “Made in Agueda” robot had to use a laptop PC operating under Linux Operating System and some low cost web-type video cameras (Creative 5) equipped with CMOS image sensors and connected to the PC through USB interfaces at the maximum rate of 25 frames/s. There are two more microcontrollers of PIC 18F252 series working in a distributed control system, interconnected through an I2C based network.

According to the contest regulation, the robot had to navigate inside a track and we use the video cameras to achieve this goal. When in action, the robot uses these cameras to evaluate the distance between the robot and the two lines that bound the sides of the track, generating a proportional error signal that is used for the control of robot direction.

In reality, when several frames exhibit image problems due to the robot movement and to the lack of power in the imaging processing system, the robot performance is limited and this was an important limitative factor in the maximum speed the robot could achieve.

An attempt to minimize this drawback was performed through additional information, like the introduction of a predictive controller that uses the knowledge of the track as the prevision model. A set of “empirical strategies” were used, such as pointing the cameras as far as possible, in order to improve the robot field of vision, being then possible to get a certain degree of anticipation on the robot control actions.

The image obtained in these conditions was low quality, exhibiting some difficulties on adapting to different light condition and to color image acquisitions. In the third phase of the contest, there were some colored obstacles (red cones signaling) on the path and the cameras showed tremendous difficulties in the processing of the color information, as they showed an enormous sensitivity to light conditions. In this case, the problem was solved through the use of ultrasonic sensors in order to identify the obstacles and navigate through them, ignoring the information provided by the cameras.

According to the scheme shown in figure 3, the control strategy of the robot was developed in order to speed-up the information that flowed between the microcontroller nodes. Therefore, the main critical navigating tasks were concentrated in one microcontroller. It received the data from the encoders, the position in the plane was updated through odometric equations and the control actions were performed by PWM interface motor power devices.

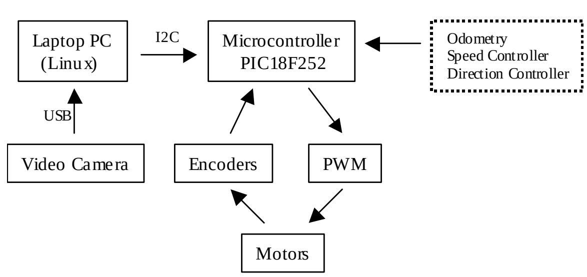

Fig. 3 - Block diagram of the autonomous navigation controller

For each error signal proportional to the distance to the track bounds, an objective imaginary point in the plain at a distance of 2 meters in front of the robot was calculated, that served as a reference for navigation purposes. By doing this, the robot continues moving during a certain period of time, even when the obtained images were not reliable enough.

Figure 4 shows the odometric path evaluated by the robot when it traveled in the half-track. The parametric adjustment was performed off-line. The results shown, for this particular case, that if the track was already known, it was possible to navigate using a mathematical model, and the cameras were used only to correct the odometric errors.

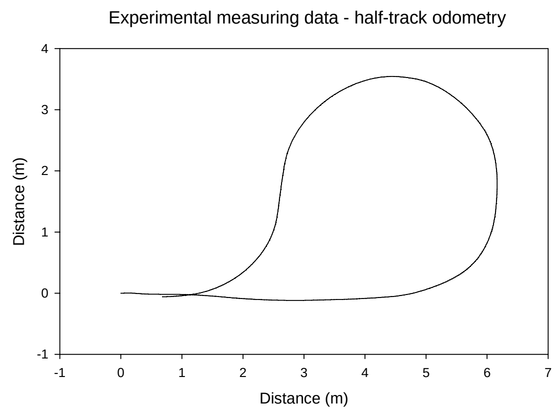

Fig. 4 – Odometric data obtained by the robot when it traveled in the half-track.

The robot was a three wheel differential steering platform with 2 electric engines powered at 24V-150W with a gear box. It weighed around 15 Kg, it was fed by 2 lead-acid battery and could operate at a speed of 2 m/s. Moreover, due to the dynamics involved, the software had to be very reliable, because if any mistake occurred at such speed, it would be very difficult to correct it.

A number of issues need to be considered for future work. To achieve better performance it may be necessary to consider a better quality imaging devices and, if possible, to use microcontrollers only for image acquisitions and processing. Moreover, the dynamic behavior of the robot is not yet explicitly included in the robot controller.

B. AVEIRO- DET (a family of robots)

The Electronics Department of the University of Aveiro (DET) has been developing, over the past few years, a family of robots based on a "*small step evolution*" philosophy and a "*simple is beautiful*" approach, responding to each year's new challenges posed by the Autonomous Driving Competition. This work has been fully developed by undergraduate students either during graduation project or as extra curricular activities.

The typical architecture of this family of robots is based on a differential driving approach with two aligned motors using a two level distributed control system guided by a vision based solution.

The purpose of the robot's underlying architecture is to explore a high degree of distribution, following the current trend in distributed embedded systems of encapsulating every function in simple dedicated nodes interconnected by a network. The aim is to improve system scalability, dependability and composability. This trend is already observed in the automotive industry, for example, with the number of nodes per car, in top models, reaching a hundred. Furthermore, a time-triggered communication model has been proposed in order to manage the complexity inherent to the communication among such a high number of nodes.

In the case of the current version of the DET's robot, the number of nodes is considerably smaller, but similar approaches as in larger systems have been used. Each node is built upon an expandable modular solution based on Microchip 18F258 μC. Basically, there is one node for each of the two motors, one node to handle the intersection and tunnel detectors, another to handle the battery level sensor, another to control front, rear and direction changing lights and finally one to interconnect the PC node (fig 5). Other nodes can be easily added, if required. The interconnection network is CAN and a particular time-triggered protocol, FTT-CAN [Pedreiras 2002], is used to manage the communication in a deterministic and flexible way. All low level modules perform all required local control routines, hiding them from the higher level control software. Motor speed control, for instance, is performed by its assigned module using a PID closed loop approach.

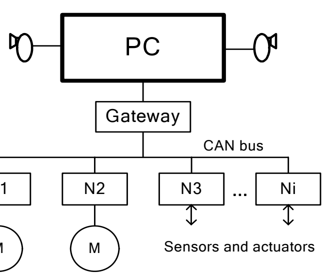

Fig. 5 – DET robot's command and control architecture

The high control system is based on a PC (running on Linux) with two interconnected video cameras. Navigation is based on reactive, pre-defined and short distance planning, using dedicated image processing routines developed for these robots. These routines include histogram normalization for segmentation decision, line detection at two predefined distances in front of the robot using a simple and fast line correlation algorithm, and evaluation of the current error regarding the ideal trajectory. Simultaneous detection of the trajectory errors at different distances are combined to estimate traction corrections based on a PD control algorithm. High level commands are then dispatched to the lower level node responsible for traction control.

Identification, by the robot, of the symbol presented in the traffic signaling panel is based on an algorithm that extracts, from the image, a set of morphological features. These features are heuristically evaluated to determine which of the signs is being presented. An auxiliary color detection approach is also used for redundancy.

Undergoing work for participation on the 2006 edition of the contest includes some major changes in the previous approach. Using the same distributed architecture, the new robot relies on independent traction and guidance systems. Two main goals are to be achieved: higher speed and long distance trajectory planning for smooth guidance control.

C. ATLAS

Since its early days, the ATLAS project at the Department of Mechanical Engineering of the University of Aveiro (www.mec.ua.pt/robotics) has had the intention of proposing robots with some kind of novelty, at least within the context of the Autonomous Driving competition. Some novelties were dropped throughout the successive editions, but the approach for decoupling the guidance and the traction units has persisted ever since. Indeed, traction has been implemented with one single motor by means of a mechanical differential gear and the adopted guidance system is the Ackermann approach. These two solutions, although mechanically more complex than traditional solutions of two differential drive motors, ensure greatest decoupling between linear and angular motion, and that is why this is the system actually used by real cars. Issues of stability, easier control and power saving justify these options.

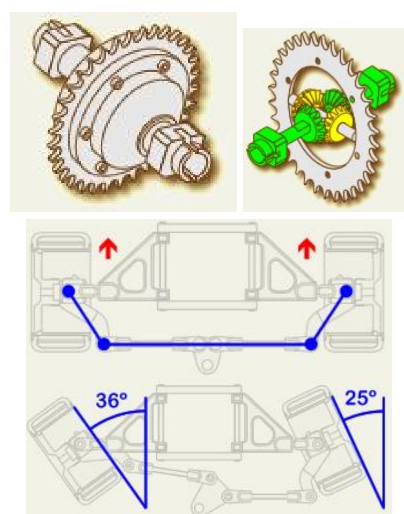

Fig. 6 – Mechanical differential gear for rear traction and Ackerman guidance [RcTek, 2001]

The Atlas III robot was a demanding piece of engineering where many details were addressed: ranging from custom machined parts, covering electrical power protection units or an electrically actuated break, up to dedicated electronics PIC-based boards for distributed processing, managed on a Linux-driven laptop with high performance Firewire cameras attached. The mechanical structure of the robot has been fully modeled in 3D but no dynamical simulation was carried out due to the complexity of the assembly plus the fact that many mechanical parameters such as frictions and similar component properties were unknown. Nonetheless, in the future, that simulation has not been excluded, especially if velocities increase very much and also if the road ground ceases to be as simple as it is currently.

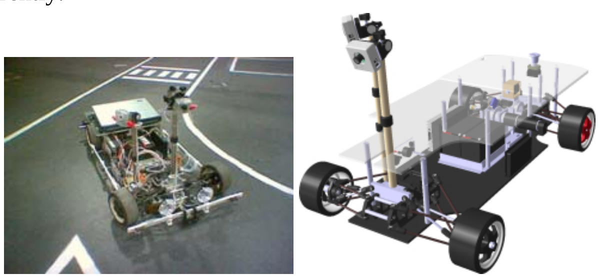

Fig. 7 – The robot ATLAS III in 2005 and its 3D model

Concerning sensorial capabilities, Atlas III uses vision for navigation and for traffic lights signs interpretation, and also some additional optical sensors to confirm the zebra crossing area and for the navigation inside the tunnel. These optical sensors are used in simple common approaches, but vision uses a relatively robust algorithm which is described briefly.

The main idea to detect the road lines is to eliminate everything from the image except the lateral lines. In few words, an artificial horizon is created in the image. By successive fills and image inversions, strange objects inside and outside the lane are discarded (Fig. 8).

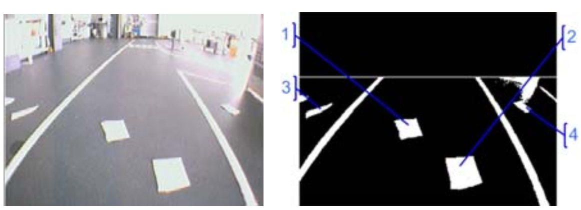

Fig. 8 - Raw and threshold image with undesired artefacts

Having the delimiting lines, an algorithm for seeking the centre of the lane has been devised an implemented [Cancela *et al.*, 2006]. Finally, some heuristics were implemented to cover for situations where only one lateral line was perceived. Zebra crossing is also detected with a related approach.

Interpretation of the traffic light panel counted both on colour and shape analysis. Operation on the HSV colour space allowed separating easily the lights, based both on hue and saturation. This gave the first iteration in light perception (Fig. 9) and then a shape-based analysis complemented the process. The combined results were extremely robust.

Fig. 9 – Sign segmentation by saturation and hue analysis

For Atlas III, the traction power vs. total weight ratio is much lower than other robots (150 W/25 kg), which is a good indicator of Atlas III performance, reminding that it achieved the second place in the national competition. On the other hand, there is a small drawback of Ackermann guidance: its reduced curvature radius when compared to single guidance wheel or the extreme ability of differential traction which allows zero radius curvatures.

The conclusion is that tradeoffs must be established and the better of both worlds may sometimes be difficult to obtain. The challenge remains open, and the future promises enthusiastic developments.

D. IQ

IQ is a tricycle-like robot, with a front driving and steering wheel. It evolved from a first version in 1998 through different modifications to handle rules of different competitions where it participated, until 2002, when it was used for the last time.

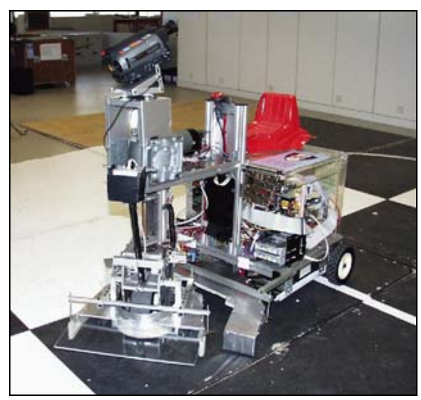

Fig. 10 - IQ robot

Besides its uncommon (compared to most other robots in the competition) tricycle kinematics, chosen on purpose to familiarize the involved students with a non-traditional guidance problem, the robot had two major distinctive features: a hierarchical state machine for behavior coordination, and a fuzzy-based track detector system.

IQ tasks are achieved through the coordination of several behaviors, implemented as hierarchical state machines. Each state of the state machine represents a running *behavior*, e.g., `follow track, check traffic light`, while transitions between states are associated to *events*, e.g., `yellow light, zebra detected`. Behaviors can be aggregated bottom-up into macro-behaviors, with an unlimited number of levels. One trivial macro-behavior would be `drive IQ`, consisting of the overall state machine coordinating the robot. This discrete-event-based model of (macro-)behaviors enables a systematic and modular deign method, as well as the possibility to analyze qualitative and quantitative properties of the task being executed, as well as a natural interface with the operator, either for task graphical design and/or to follow task execution (e.g., by sequentially highlighting current states and occurring events).

IQ track detector operates over a track image periodically updated by a vision camera installed in the vehicle front. The algorithm selects two image rows based on past information and classifies each row information based on three features: black/white contrast over the row, image edges strength and track width. Feature classification is based on fuzzy membership functions. A 1-D image derivative is determined for each image row, and several pairs of derivative maxima and minima are graded with respect to the three features. The grading is subsequently combined by a fuzzy decision making algorithm, whose output (shown in Fig. 11) can be used to select the most plausible track reference points over each row and fit a straight line to those points. From the straight line, the track position and orientation, as well as the track selection fuzzy degree of confidence, can be obtained [Portela et al, 2000]. The track position and orientation outputs of the track detector are fuzzified and fed into a rule-based table resulting from the controller discretization. The controller output is the set point for the steering angle control loop, a PID position controller, which guarantees the required steering accuracy. The fuzzy controller was relatively easy to tune, based on geometrical considerations and enumeration of all possible vehicle-track relative situations. The driving speed is set from the recognition confidence level of the track parameters, which is also based on fuzzy processing. The track detector proved to be very more robust to the environment light changes and to avoid a time-consuming number of threshold calibrations made along the whole track, which would be required otherwise.

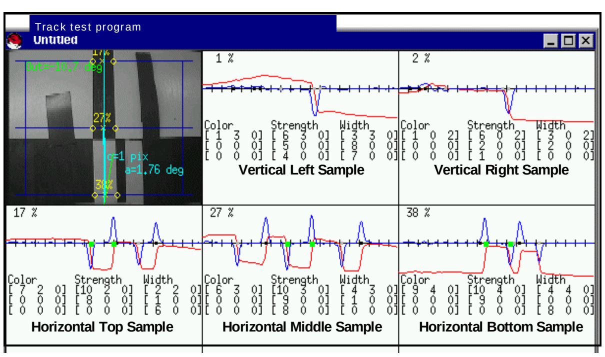

Fig. 10 – Results of IQ track detector application to several rows of a sample image.

IV. CONCLUSIONS

The objective for competitions must remain within the research interests of a particular area. The entertainment value is important but it is very disappointing to put an enormous research effort reduced to performance in a particular event.

A competition has to be a part of a larger and well organized research program.

It is also important to participate in competitions that are embedded on larger conferences, because it allows the presentation of the research behind the competition, in the right forum to discuss related ideas [Bräunl 1999]. Advantages of these competitions include a higher level of motivation, the possibility to involve students in multidisciplinary teams and the fact that this competition constitutes open ended engineering problems that allow students to integrate knowledge from a variety of engineering courses [Manseur 2000].

In the Portuguese Robotics Open Autonomous Driving Competition we tried to keep a balance between the scientific challenges involved and the entertainment value. For the scientific challenges, the main goal is that, year after year, new challenges are added to cope with situations that are closer to the real life driving.

For this purpose we use tracks to guide like cars like in normal roads, and this year that are two lanes in the road, forcing the robot to change from line in the presence of an obstacle.

The pedestrian zebra cross is kept since the contest first edition to make the robot behave differently in function of the ground traffic signals.

Traffic lights are used to simulate real traffic lights.

Since the beginning we there is a tunnel in the track to force the robots to change their navigation system as well as in future, autonomous vehicle will have to change their guidance according for instance, the unavailability of a GPS signal, forcing the robot to align itself with other physical references in the environment.

The work zone was introduced to force again the robot to change its guidance rules according to an unexpected event. In this challenge, both the work zone and obstacle locations are not known before the robot start.

These challenges have been successfully handled by Robotica robots which, year after year, have been able to cope with these increasing challenges, leading the involved research community to cope with current robotic challenges. The development of these robots involved many interesting developments on areas as spread as sensor fusion (Made in Águeda) image processing, structure modeling (ATLAS), distributed systems development and integration (DET-UA) and discrete event systems (IQ).

In all editions it was possible to find at least one robot that was able to finish the competition with a perfect score meaning that it achieved all tasks successfully.

The Portuguese Robotics Open is now in its 6th edition, increasing the difficulties every year, coping with further scientific goals and being glad to associate these achievements with activities that are important for science dissemination among general public.

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