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Hybrid Control Architecture for Navigation of Unmanned Underwater Vehicles

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ABSTRACT

In the present paper, a hybrid architecture based on multi-agent systems is proposed based on a layered system. This architecture presents qualities of modularity and scalability. It is also developed a methodology for trajectory tracking based on the generation of a reliable virtual space, on which the navigation takes place under operative conditions (safety and effectiveness). Time processing operations reduction is expected during the inspection.

1. Introduction

The unmanned autonomous underwater systems have had an increase in their autonomy capacity during the last decade (Insaurralde and Lane, 2012), both from the energy supply and the decision capacity point of view. This autonomy enables the possibility of carrying out reliable and secure applications with this type of systems.

The robotic systems inclusion in the underwater environment is highly complex, mainly due to variable and unpredictable dynamic behavior that have a significative impact on the different activities that can take place on. One such complex activity, is the underwater cable inspection (Jacobi and Karimanzira, 2013; Asakawa et al., 2002), because of the difficulty in operating in a harsh environment. This constitutes a research line of growing interest.

Inspection systems for underwater cables have evolved with the development of underwater robotic systems. The conventional underwater operational trend can be divided in two groups: one is the underwater cable inspection by divers and another is the inspection by using autonomous underwater vehicles. The former is the risky one since divers are exposed to the inherent dangers of high depths. The latter is made by using underwater vehicles that assist a human operator in a dangerous operation. Basically the underwater vehicles (Yildiz et al., 2009/12/) develops location and positioning tasks, in order to improve inspection of submarine cables through underwater vision systems (stereo-vision).

Due to the high complexity of these applications is essential, its development under a control architecture that contains implicitly characteristics of modularity and scalability, which allow transactions between architecture levels. Today unmanned autonomous systems have high restrictions to perform these inspection actions. These restrictions are referred to the execution time of image processing routines, scanning blocks, etc.

In this paper, we propose a cooperative multi-agent architecture (Panait and Luke, 2005; Woolridge and Wooldridge, 2001; Russell and Norvig, 2003) that comes from the conventional concept of hybrid architecture based on a layered system divided into behavioral groups: a reactive behavior, in which the system should react in an automatic way to a particular

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event, i.e. if an object is detected the obstacle avoidance system modifies the trajectory of the vehicle in order to avoid an impact, and a deliberative behavior, in which it is evaluated different possibilities and selected the most suitable in each situation, for example, the generation of a path between two points depending on consumption, etc.

2. The Problem

As previously stated, the aim of this work is the inspection of underwater cables by means of autonomous unmanned systems. To this, the vehicle should track the cable and evaluate the data captured by the instrumentation in order to determine the cable defects.

The conventional methodology for inspection of underwater cables consists of a seabed cable tracker based on data acquired from a frontal sonar. To do this, companies uses unmanned underwater vehicles that detects the cable in advance and generates the reference trajectory for the vehicle. However, in our proposal, we generate a virtual trajectory based on SSS data that predicts the virtual trajectory by means of previous data. In this way, we propose an architecture that deals with the underwater cable tracking using SSS data.

The underwater cables internal structure usually incorporates different types of steel wires that prevent abrupt changes in the direction of the cable lying on the seabed. That is why the trajectories of these cables are expected to be smooth and that aspect is taken into account in the tracker design in the sections below.

2.1. The Underwater Vehicle

In the present work, in order to solve the cited problem a torpedo-shaped vehicle is used, in which two different types of sonar are mounted: a side scan sonar (SSS) (Bagnitsky et al., 2011//) and a navigation sonar (NS). In this way, the vehicle is able to acquire data related to the seabed, on both sides of the vehicle. The SSS coverage allows us to detect approximately 1 meter from the seabed width. The NS is situated at the bow side of the vehicle and the SSS is placed at the central part of the vehicle.

The image study is performed by using computer vision techniques. Thanks to the NS image of the environment, it is possible to detect objects in advance, both dynamic and static ones, providing a reliable and secure path. It is likely that in the SSS image different objects lying on the seabed appear, in that study it should be taken into account the acoustic shadows study, since it provides characteristics of the objects. As previously mentioned SSS are attached to the central part of the vehicle providing information of objects within the zone determined by the detection sonar angle. This detection zone depends on the depth, therefore there are higher and lower limits for the reliable detection of underwater cable.

After analyzing and detecting the cable by using SSS, new position points corroborating the correct path are determined by a navigation block that will be described below. Therefore, the vehicle navigates from the theoretical development of a trajectory obtained by adjusting, the acquired SSS points, by a function. It is important to note the existence of a relationship between the generation of the trajectory and sudden changes in speed equipment, since these new generation points depend on the vehicle speed and therefore the position obtained at each iteration.

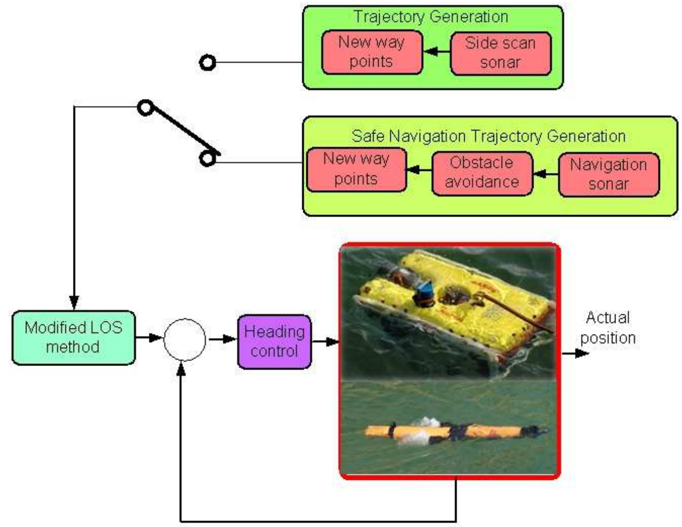

Figure 1: Basic Architecture for underwater vehicles control.

2.2. Basic Architecture

Figure 1 shows the basic architecture for underwater cables by using a torpedo-shaped vehicle with the characteristics indicated above. This architecture is based on 4 modules. A path generation module for tracking the underwater cable, which is capable of the generation of a theoretical path from a function that combines all previously acquired points for the following set of waypoints, a safe navigation system, able to analyze and avoid anything that is or can intercept trajectory set by the previous module, a decision system, based on ECA rules (event-condition-action) (Almeida Emanuel and Dawn, 2005), capable of modifying the behavior of system by changing the operating mode of navigation to safe navigation in the instant detection system shows a potential danger and finally, a monitoring path system (tracker path), to faithfully follow each of the waypoint provided by the navigation module in charge of reducing the transverse error path.

3. Proposed Architecture

From the mentioned basic architecture, it has been developed a complex architecture based on multi-agent systems framework. Figure 2 shows the different modules framed within each layer and their corresponding agents. There are different classes of agents responsible for different tasks, a group of them are responsible for the acquisition of environmental data and vehicle positioning. Others are in charge of controlling the dynamic behavior of the vehicle in different situations. Finally, there is a group that provides cohesion to the different modules, the supervisors agents, whose functionality is to join all the groups, by planning and controlling the different blocks.

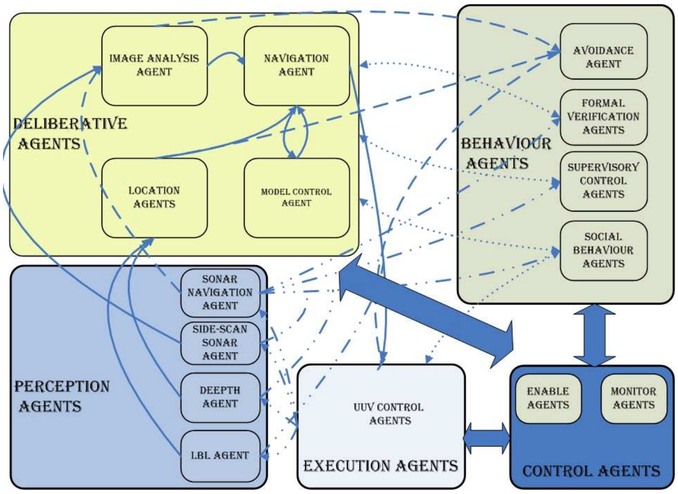

Figure 2: Multi-agent architecture.

It has been included an agents control block for the correct operation of the system, which enables/disables the modules depending on the overall system performance. That is, the supervisor control block (Ramadge and Wonham, 1984) modifies the overall performance in order to avoid undesired behaviours. A clear example is the disabling of navigation block when the vehicle is within the obstacle avoidance block.

Figure 3 exhibits the modules and sub-modules that comprise the system, along with the data that are transmitted among them. As indicated above, the proposed architecture is arranged in layers, therefore, these modules should be located in their correct layer.

The deliberative layer has the navigation modules, the loss cable modules, meanwhile the reactive layer, we can find the obstacle avoidance modules and the path tracking modules.

The acquisition and processing images module sonar is common to both layers, since the data obtained by the SSS is used in the deliberative layer while the NS is fed by its own data.

3.1. Modules

The architecture consists of five main modules. The modules time constraints are different, while some of them work on real time as the execution module does, other systems are latent awaiting its habilitation from an event, the event of the latter type are the Obstacle Avoidance modules and Loss Cable Modules. This section summarizes each of the modules of the proposed architecture:

The Navigation module is responsible for the generation of a reliable and safe path for the vehicle. In the acquisition and image processing module it is obtained the cable position and it is transferred to the earth-fixed coordinate system. The system generates a path from the points acquired in the previous stages, for this, the data obtained are used in a such a way that the decision system does not follow the path defined when there is a large variation in the speed. When the path of the cable has been defined, which is a speed function, a feasible path for the vehicle is generated by smoothing the path by means of B-splines. The objects detection zone is calculated from the B-spline definition (Pedraza et al., 2009/). This can be done by solving the next equation:

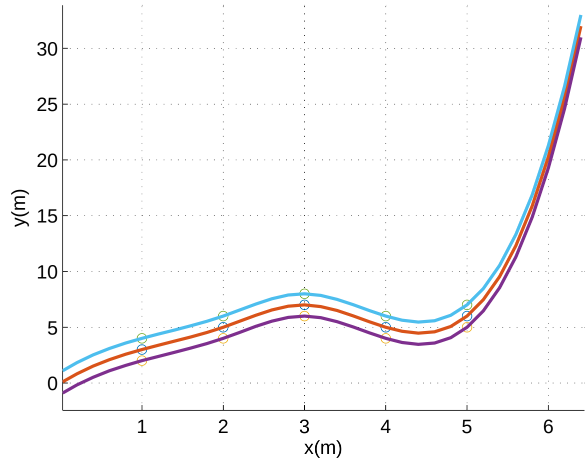

Figure 4: Detection area (area between blue and purple lines) and theoretical path (red line)

$$P(t) = \sum_{i=1}^{n} P_i N_{i,j}(t) \tag{1}$$

being $P(t)$ the position of the vector along an m-dimensional curve as a function of $t\epsilon\Re$, a spline curve of order j, $P_i\epsilon\Re^m(i = 0,\ldots,n)$ the control points and $N_{i,j}(t)$ are the normalized B-spline basis functions of order j and knot vector $\Xi = \{x_0,\ldots x_{n+k}\}$. These B-spline functions are defined by the Cox-de Boor recursion formulas,

$$N_{i,j} \equiv \begin{cases} 1 \; if x_i \leq t \leq x_{i+1} \\ 0 \; for\ the\ rest\ of\ the\ cases \end{cases} \tag{2}$$

and for all $j > 1$

$$N_{i,j}(t) = \frac{(t - x_i)N_{i,j-1}(t)}{x_{i+j-1} - x_i} + \frac{(-t + x_{i+j})N_{i+1,j-1}(t)}{x_{i+j} - x_{j+1}} \tag{3}$$

where t is the time, x is position of the vehicle in the horizontal axis.

Then by applying expressions (1), (2) and (3), we obtain a secure zone as can be seen in figure 4.

In this way, from the cited zone we can establish a secure volume for the system operation (Figure 5). By overlapping the different layers, limited only by the depth and accurate characterization of the seabed objects.

The Image Sonar Control Module, feeds the navigation and obstacle avoidance modules. By studying the SSS images, the cable position on the seabed is determined. Additionally, by studying the images of the NS it is determined the existence of objects in the path of the robotic system.

The Obstacle Avoidance Module, defines a reliable path to avoid a potential impact of the vehicle, determined by the

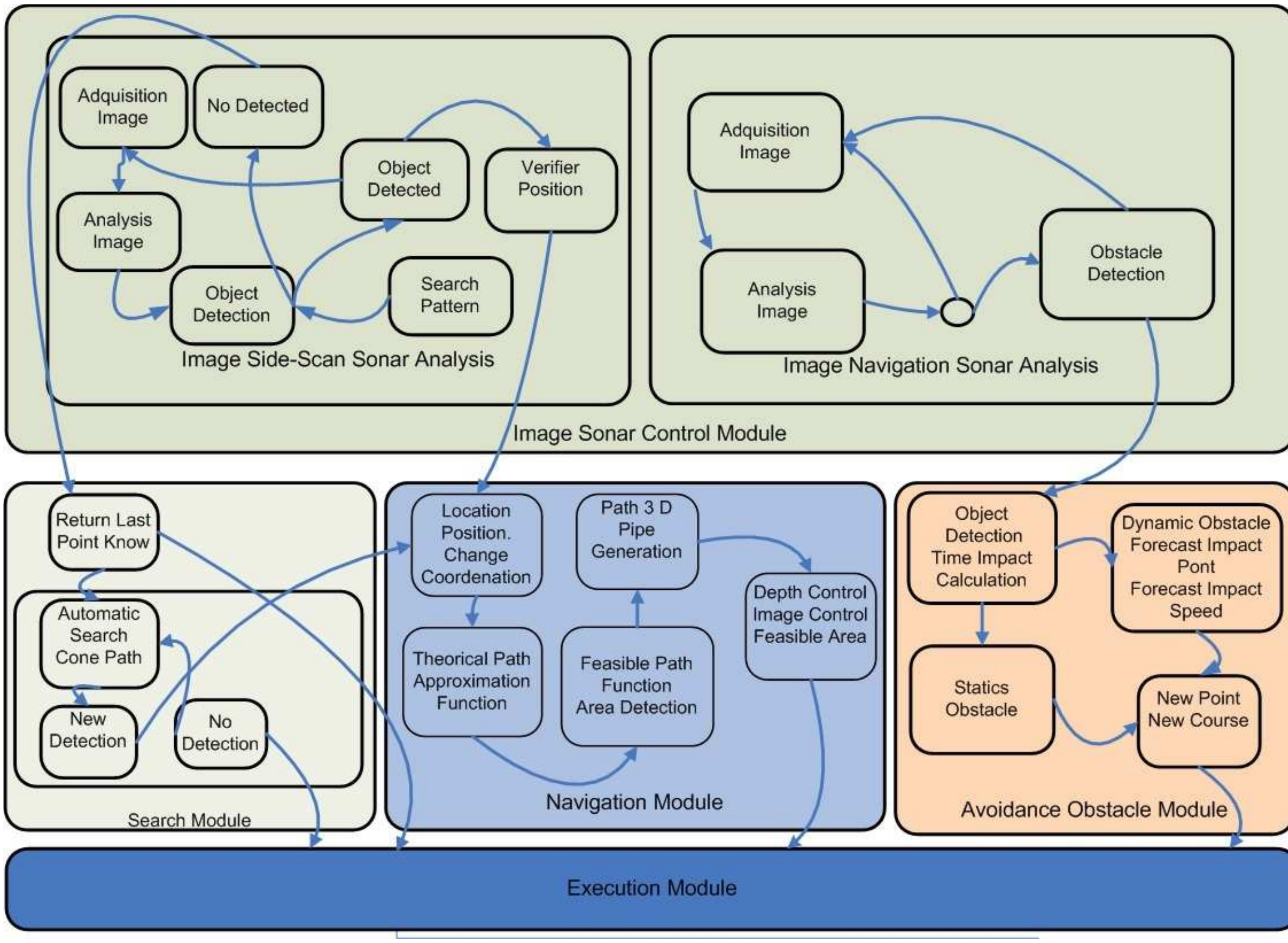

Figure 3: The proposed control architecture.

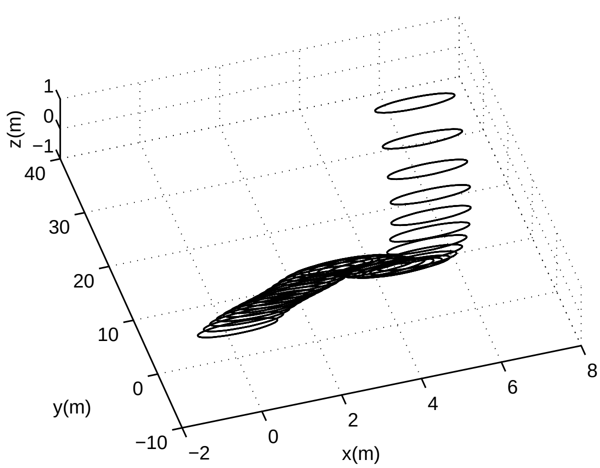

Figure 5: Volumetric safe path.

path provided by the navigation module and any object that is in the frontal area of the vehicle.

Every single detected object is assumed to be static and it is evaluated with the following acquired images in order to determine if this assumption is accepted or rejected. The following acquired images analysis is made in two steps, in the first step, the avoidance module evaluates the relative position between the vehicle and the detected object, and in the second step, it is verified if the proportional shape of the object has been modified by checking a predefined threshold. In the affirmative case the initial assumption is rejected and the object is considered to be dynamic.

After this, the trajectory of the dynamic object is calculated and the potential impact time is determined. For both dynamic and static objects, the obstacle avoidance module calculates the new path and sends it to the execution module.

The Search Module. When this module is accessed, it is loaded the last known cable position and then established a secure path to this point, after the vehicle reaches it, the search cable algorithm sets up a conical path for the vehicle, starting from the last known point to the theoretical area determined by the navigation module. Once determined the cable again, the system deletes the set of points corresponding to the previous path and the cycle begins again. In case of not finding the vehicle, it ascends to the surface and transmits the last known position to the control station.

The Execution module is composed of two modules. A decision module, in which the action to be made is determined in every moment. It is an event-based system that depends on the behavior of the system. If the obstacle avoidance module detects an object, it is generated a path to avoid the object. The control returns to the navigation module once the vehicles has avoided the object. Another module corresponds to the path tracking algorithm, a modified LOS (Line of Sight), whose aim is to reduce the transverse error path among each of the points obtained by the Navigation and Obstacle Avoidance Modules.

3.2. Features of the Architecture

In the proposed architecture is used a cooperative multi-agent platform, which consists of a group of agents that allows the concepts of modularity and scalability required for such applications.

The modularity of the architecture allows an increase in the capacity of interchangeability and connectivity among modules avoiding incompatibilities and risks of understanding among them.

The scalability of the system allows the reduction of potential errors, provided by the level change or environment. One aspect of paramount importance is the necessity to develop different strategies for operational control. For that purpose it is estimated that a verification module will be needed in the system. Thus the trajectory generation module is based on data previously verified and whose interpretation is without potential inconsistencies that lead indefinite answers by the control system. It is also interpreted working temporary restrictions of the layers, reducing delays caused by the interpreters of different levels in launching interruptions or subroutines for different scenarios in processing data received from sensors. The using of this cooperative multi-agent architecture limits these delays.

4. Simulation Results

Based on the previous sections it has been implemented in the Matlab/Simulink environment a finite states machine for the navigation execution module simulation. Based in a previous work (Francisco J. Velasco and Antolin, 2015), we have implemented a manoeuvring model for a guidance system based on the modified LOS method stated in our previous work. The ocean currents have been simulated by including the current-induced forces and moments in the dynamics equations. One way of doing this is to assume that the equations are represented in terms of the relative velocity. The way in which the contribution of the currents has been implemented is found in Fossen (2002).

The results for the guidance system are shown in figure 6 where it is compared the conventional LOS performance to the modified LOS performance. It is observed a reduction in the cross track error when the modified LOS is applied for the given reference waypoint vector ([0,0;20,25;-20,30;-30,40;20,70;0,80]).

Figure 7 shows the trajectory generation for the torpedo-shaped vehicle. The dashed green line depicts the path given by the navigation module, as it is seen it is almost entirely within the area bounded by the cable detection beam range of the SSS at a constant depth.

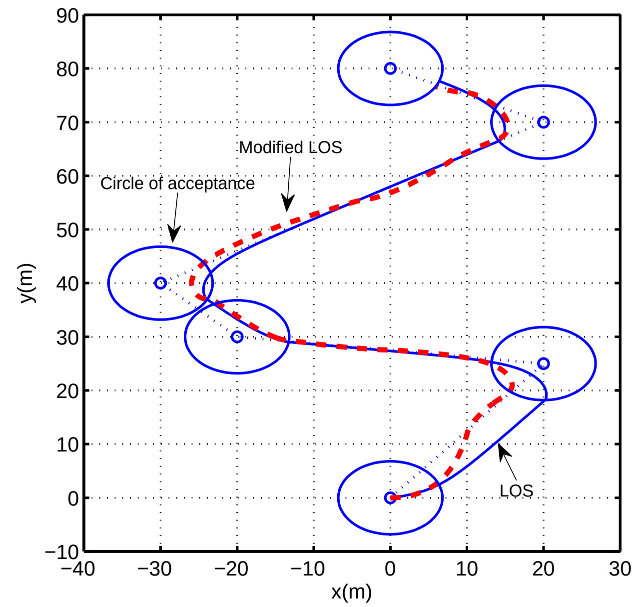

Figure 6: Conventional LOS (blue line) and modified LOS (dashed red line) performance with currents (0.3m/s) for the vector of waypoints reference=[0,0;20,25;-20,30;-30,40;20,70;0,80].

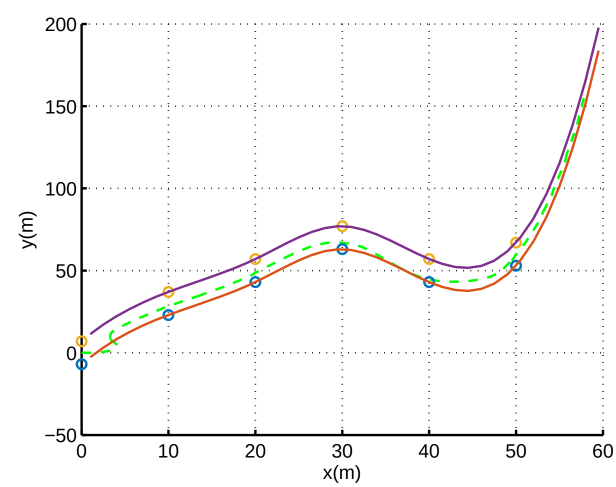

Figure 7: Detection area (between blue and red lines) and simulated track (green dashed line) for the torpedo-shaped vehicle.

In the figure 8 it is shown the reliable navigation volume for various depths shown in each of the positions achievable by the underwater vehicle within the detection range.

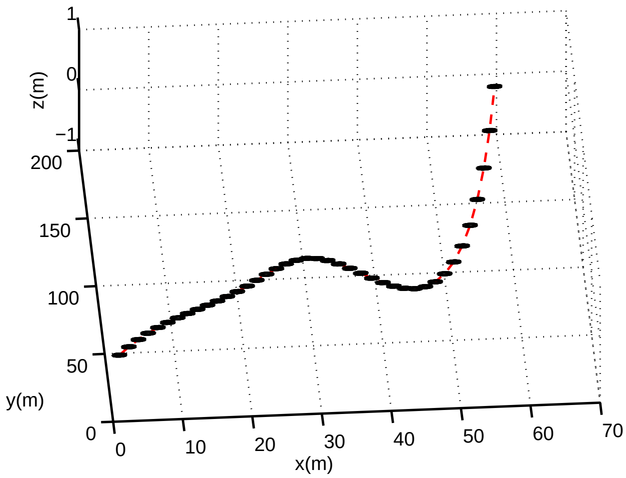

Figure 8: Detection volume and trajectory developed by the vehicle.

5. Conclusions

In this paper we have proposed a multi-agent based architecture that allows to respond to the preset time restrictions, affecting both time consuming and tracking for underwater cables inspection using autonomous underwater vehicles.

The use of this type of vehicle in recent years is due to the breakthrough in their autonomy, both from an energy standpoint and decision-making capacity.

Through this proposed architecture, adding the methodology based on the generation of a tubular virtual space, we pursue, reducing time identification and improving the tracking performance of the object, besides giving a more reliable and safe operation.

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