FUZZY STEERING CONTROL OF A HYDRAULIC TRACTOR AND LASER PERCEPTION IN OBSTACLE AVOIDANCE STRATEGIES

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Abstract

Present work describes the implementation of a fuzzy steering controller for safe obstacle avoidance in unmanned navigation of a robot-tractor. Safety is warranted by the laser perception of the environment. The fuzzy controller integrates human knowledge on vehicle driving in the presence of unexpected objects, in a set of linguistic expressions. This steering control strategy is extremely useful for the reactive piloting of a commercial tractor retrofitted at the IAI-CSIC warehouses, to perform autonomous navigation in agricultural and open field environments. Some results are displayed on a global geo-referenced map of the IAI-CSIC campus in Arganda del Rey (Madrid), to show the real time avoidance behaviour.

Keywords: Fuzzy steering control, Robot-tractor, Hydraulic actuator, Avoid obstacle, laser perception.

1 INTRODUCTION

The development of an autonomous outdoor vehicle requires the integration of a plethora of subsystems and knowledge from multiple fields. From the mechanical design, control of the actuation systems, sensors and perception mechanisms, to the cognitive architectures, required to navigate in dynamic environments.
The automation of tractor navigation is still a challenge for many tasks, being one of them the selective distribution of pesticides, as it greatly reduces environment and human risks [4], [16]. The integration of sensors, actuators, processors and wireless communication systems would shift repetitive and sometimes risky low speed manual operations, to tele-operation and autonomous navigation of rural vehicles, such as tractors [14]. In addition, real-time perception of the environment is necessary to ensure safety in environments where operators and vehicles work together.
On the other hand, fuzzy controllers have been widely applied for industrial processes due to their simplicity and effectiveness, as non-analytical model that embed human expert knowledge [1], [2], [10], [12]. They have been successfully used for a wide number of applications dealing with complex and non-linear processes, wherein they are proved to be robust and less sensitive to parametric variations and noise than conventional controllers [3], [18].
Finally, laser range finders are fundamental to get a safe navigation in outdoor environments [6], [17], [7], [19]. Safe and efficient obstacle avoidance strategies would be used in multi-objective autonomous navigation. To this aim, a fuzzy steering controller and a laser perception system have been developed and tested in a commercial hydraulic tractor.

2 EXPERIMENTAL SYSTEM

2.1. THE ROBOT-TRACTOR DEDALO

The vehicle used, as experimental platform, is a commercial tractor (AGRIA HISPANIA, S.A.) adequately retrofitted to get two navigation modes: teleoperated and autonomous GPS guided, in addition to the manual drive, Figure 1.

Figure 1: Hydraulic tractor, namely DEDALO.

The steering, the brake and the clutch of the tractor are activated through a multifunctional A/D PCI card (Advantech PCI-1710 series), plugged in the onboard industrial PC and allows the powering of the electro-valves. The fuzzy steering control strategy has been implemented with Matlab Data Acquisition Toolbox [11], which permits accurate communication between the onboard PC and the A/D card to manage both digital and analog signals.

The low-level control of the tractor is accomplished, managing the hydraulic actuation system based on the tractor pump, the hydraulic cylinders and the electro-valves. This hydraulic system gives pressure to the brake and clutch cylinders to shift brake and clutch actuators. The steering has been automated with an electro-valve since the tractor was steering hydraulic power-assisted. The whole hydraulic actuation system is managed by: (i) automatic/manual trigger, (ii) hydraulic pressure control, (iii) clutch electro-valve signal, (iv) brake electro-valve signal, (v) steering electro-valve control (left and right); to convert the electrical signals in mechanical displacement of the cylinder piston rods.

The control of the position of the brake and clutch is on/off, whereas the control of the position of the steering is gradual and measured by means of a potentiometer sensor coupled to the steering cylinder. The analog voltage of the potentiometer is read by the A/D PCI card. The conversion from analog voltages to precise steering angles is performed through a calibration process, by measuring several steering angles with its corresponding voltages. The results are shown in Table 1.

Table 1: Wheel angle and potentiometer measurements.

Wheel steering angle (degrees)	Potentiometer Voltages [V]
-35° (maximum left steering)	4.57 V
0° (no steering)	3.42 V
+35° (maximum right steering)	2.41 V

According to these measurements, a quadratic calibration function (1), to calculate the voltage at any steering angle in degrees.

$$V = 5.71e^{-5}\alpha^2 - 0.0309\alpha + 3.42 \quad (1)$$

So, the steps of the automatic steering control strategy are: (i) reading of the initial voltage from the analog port, (ii) introduction of the orientation of the target position in the Graphical User Interface (GUI), by the operator of the robot-tractor, (iii) calculation of the voltage corresponding to the orientation of the target position, (iv) activation of the suitable electro-valve, to reach the target orientation, and (v) closing of the steering electro-valve once the target voltage is attained . As an example, lets the robot-tractor going straight ahead and the steering voltage being 3.42 volts. The tractor orientation at the target position implies a turn of 20° to the right, which corresponds to 2.82 V. Then,, the steering electro-valve is activated to shift the steering cylinder piston rod, so as the potentiometer voltage reach 2.82 V.

2.2. ONBOARD PROCESSOR

The onboard processing system is an industrial laptop, Kontron NotePAC Intel Core Duo 1.66 GHz processor, 2 GB RAM, with a PCMCIA WLAN. Initialization and visualization processes are executed on an external Tablet PC (Fujitsu-Siemens Stylistic ST5112), Intel Core Duo Processor (1.33 GHz) with 3.24 GB RAM. This Tablet PC has similar characteristic to a PDA but larger-size screen and higher processing capabilities [13], allowing a more complex user-interface, usually required in outdoor environments.

2.3. LASER RANGE FINDER

Laser scanners are increasingly used in automation and robotic applications as a depth sensing device useful for safety requirements. They have been tested in agricultural applications for measuring plant growth rate, tree volume, 3D imaging, and pattern recognition [9].

To reach safe piloting, a laser range finder has been installed in the tractor to get real-time depth images of the environment objects [15]. The 2D laser range finder emits an infrared laser beam, and receives the signal reflected by the object closer than 80 m .The laser provides polar coordinates, with 0.5 degrees of resolution in a 180° field, Figure 2.

Figure 2: Laser range finder in the tractor.

2.4 WIRELESS NETWORK FOR REMOTE CONTROL

Man-machine communication is nowadays accomplished with low cost wireless networks (WLAN), which can be easily installed and operated. In current work, communication relies on a Wireless Local Area Network (WLAN) that follows the standard IEEE-802.11b. The integration of the wireless communication enables the onboard processor to be accessed via the Intranet/Internet, from any WLAN workstation.

3. CONTROL ARCHITECTURE: AMARA

A cognitive architecture of agents of behaviour has been implemented as a suitable framework to deal with all the information acquired by the sensors, the domain knowledge, and the control processes [5]. Perceptual and motor processes are encapsulated under the framework of agents of behaviour [4]. The system offers three levels of competence with distinct system representation, and two ways to share information among processes: by message passing among agents and through shared memory. The system is implemented under the client/server paradigm, where processes running on different machines are appropriately connected by win-socket drivers and standard protocols. The main agent is the SERVER that runs on the onboard processor. This agent acts as a data server and as a client, sending sensor data upstream and accepting action commands during the run time. In addition to SERVER agent, several agents have been designed to mimic the sequence of actions performed by the human drivers. Agents can be ascribed to different competence layers. The middle layer is the piloting layer composed of three basic reactive agents of behaviour: ADVANCE, AVOID and STOP, Figure 3. They are coordinated by the adjacent upper level motor behaviour, namely WANDER. This motor agent relies on the perception cues of the working domain such as, Point, Obstacle, Local and Global maps, which are elaborated from raw sensor data, context information and Web services. Real-time interactions with the world, through the sensors, guide the activation of the reactive layer: {STOP, AVOID, ADVANCE} from a specific upper level behaviour.

3.1 AN AGENT OF BEHAVIOUR: WANDER

The module developed in current work, is a motor agent, namely WANDER. This agent implements the fusion of raw and elaborated data and representations, such as laser, GPS, objects and local and global grid map, respectively. From GPS and raw laser data, tractor position and depth of close objects are obtained by the perceptive agents, DETECT POSITION, DETECT OBSTACLE in addition to the deliberative agents DOWNLOAD GLOBAL MAP, GENERATE LOCAL MAP and VISUALIZATION.

3.2 AGENTS AND INFORMATION FLOW

In the AMARA architecture, perceptions flows bottom-up from raw data to abstract structures, and actions flow top-down from human commands to the hydraulic actuators, integrated in DEDALO tractor, Figure 3. The local grid map generated from raw laser data has a temporal persistency of about 2 seconds, and a spatial resolution of 20 cm, both much lower than the one obtained with raw laser data but with a higher confidence degree on the detected obstacles. These processes are embedded in the agent GENERATE LOCAL MAP that generates a perceptual structure, Object, defined through a set of features. The agent DOWNLOAD GLOBAL MAP is devoted to the acquisition of a georeferenced map of the working domain. This last agent is considered a deliberative one, and it delivers a data structure in the shared memory to be used by others agents, such as the agent VISUALIZATION.

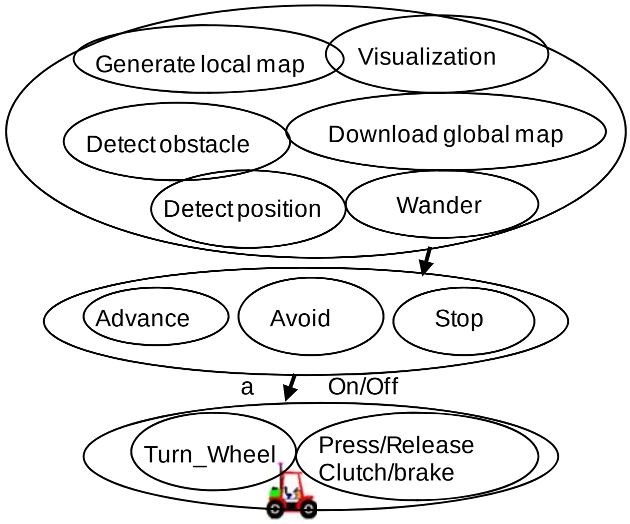


Figure 3: AMARA architecture.

4 FUZZY STEERING CONTROL IN OBSTACLE AVOIDANCE

The difficulty of deriving an analytic model of the steering system, as it is composed of several subsystems, recommend the design of a fuzzy controller, where the model is formulated by a set of linguistic rules expressed in natural language. These control rules establish the relationships between inputs and output [8], and encapsulate the non-linear dynamics of the whole actuation system to control the steering of the front wheels.
The Knowledge Base has been designed with the aid of MATLAB, to speed up the design and tuning of the fuzzy controller. The Fuzzy Logic Toolbox allows the definition of variables, linguistic labels and rules.

There are two types of variables: input and output. The first one accounts for the state of the system and the second for the control actions to be performed. The differentiation occurs implicitly, as variables defined as inputs always appear in the rule antecedent and outputs in the consequent. The implemented fuzzy-logic controller has two input variables: the “Obstacle aperture angle” and the “Obstacle distance”, and one output variable: the “Wheel Angle”.
Each variable is described by a set of linguistic terms, which are represented by means of membership functions, trapezoidal in this case. The membership functions are fixed in agreement with the expert knowledge and the empirical tests initially performed. The linguistic values of the two input variables are:

- “Obstacle aperture angle” {Small, Medium, Large}, Figure 4.
- “Obstacle distance” {Near, Far, VeryFar}, Figure 5.

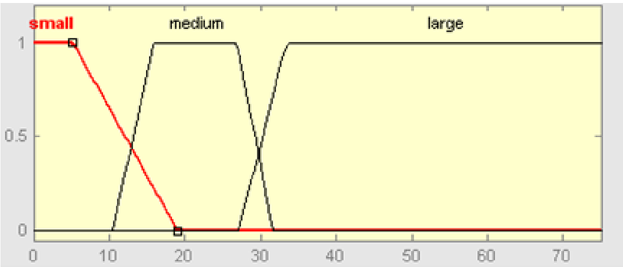


Figure 4 : Membership functions of the linguistic values of the “Obstacle aperture angle (angle)” variable.

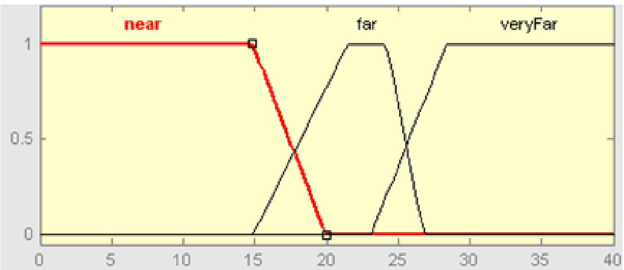


Figure 5: Membership functions of the linguistic values of the “Obstacle Distance” (distance) variable.

Five linguistic values, unevenly distributed along the universe of discourse of the variable, have been defined for the output “Wheel Angle”, Figure 6: {VeryVerySmall, VerySmall, Small, High, VeryHigh}.

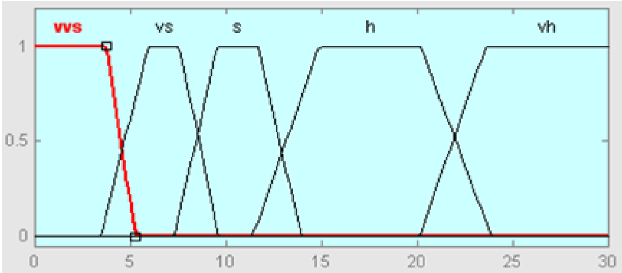


Figure 6: Membership functions of the linguistic values of the variable “Wheel Angle” (angleOut)

The Knowledge Base is composed of a set of propositions of the type: IF {(A is a) AND (B is b)} THEN {(C is c)} with a number of conjunctive constraints in the antecedent and only one constraint in the consequent. The designed fuzzy steering controller is composed of rules of the type: IF (“Obstacle aperture angle” is small) AND (“Obstacle distance” is near) THEN (“Wheel Angle” is small). All possible combinations of the variables terms, are represented in a fuzzy associative memory matrix, Table 2. The Knowledge Base of the fuzzy steering controller is displayed in Table 3.

Table 2 : Input, output matrix

Angle\Distance	**Near**	**Far**	**Very far**
Small	VeryHigh	High	Small
Medium	High	Small	VerySmall
Large	Small	VerySmall	VeryVerySmall

Table 3: Knowledge Base of the fuzzy steering controller

R1. If (angle is small) and (distance is near) then (angleOut is vh) (1)
R2. If (angle is small) and (distance is far) then (angleOut is h) (1)
R3. If (angle is small) and (distance is veryFar) then (angleOut is s) (1)
R4. If (angle is medium) and (distance is near) then (angleOut is h) (1)
R5. If (angle is medium) and (distance is far) then (angleOut is s) (1)
R6. If (angle is medium) and (distance is veryFar) then (angleOut is vs) (1)
R7. If (angle is large) and (distance is near) then (angleOut is s) (1)
R8. If (angle is large) and (distance is far) then (angleOut is vs) (1)
R9. If (angle is large) and (distance is veryFar) then (angleOut is vvs) (1)

Matlab Fuzzy toolbox allows the design and visualization of the different rules and membership functions to adjust their numeric values to the restrictions of the control system. Figure 7 illustrates an example of each rule activation and output evaluation. The defuzzification algorithm used is the Centre of Mass, that weights the output of each rule in the Knowledge Base with the truth degree of its antecedent, to derive a mean crisp value. In the Figure 7, the two input values are: (i) “Obstacle aperture angle”, 30.6°, and (ii) “Obstacle distance”, 18 laser cells in the grid map. This grid map is built to represent detected objects, with a higher temporal persistency than the laser snapshot. Each cell represents an area of 400 cm^2 (20 cm x 20 cm)), that corresponds to a laser distance increment of 3.6 meters. Finally, the Centre of Mass defuzzification algorithm gives an output of 12° to the “Wheel angle”, to avoid the detected obstacle.

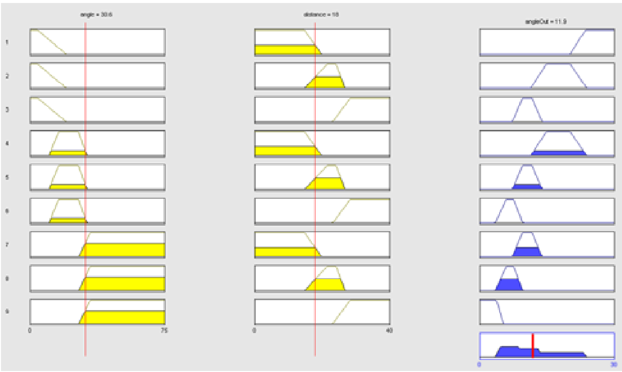


Figure 7: Rules activation and corresponding output

The control surface of the fuzzy steering controller is represented in Figure 8, with a control cycle of 200 ms, close to that of the laser snapshot.

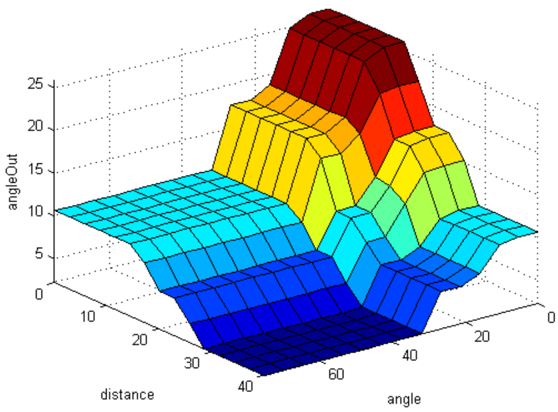
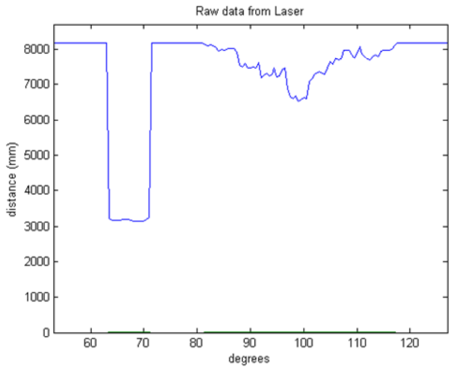


Figure 8: Control surface of the fuzzy steering controller.

5. RESULTS

The performance of the fuzzy controller has been tested in real time, under different working conditions, in the whole steering angle range [- 30° to + 30°]. The Figure 9 shows a visual and laser images of a scene. The analysis of the raw laser data has been accomplished with MATLAB [11], due to the ease and fast development facilities offered by its multiple toolboxes and libraries in the initial stage of the development of a program. The original laser data, in polar coordinates, are processed to represent orientation (degrees) in the abscissa axis, and distance to the reflecting object surface in the ordinate axis.

(a)



(b)

Figure 9: (a) Colour visual image, (b) laser image.

The local grid map in Figure 10, represents the environment in front of the robot to a maximum distance of 8 meters, corresponding to the scene displayed in Figure 9. Yellow-green colour rectangles mark the points where the laser detects an obstacle in consecutive snapshots. To give more security and accuracy to the obstacle detected with the laser, an orange perimeter contour of one cell width surround every yellow obstacle in the local map. The tractor is represented by azure object at the bottom of the map.

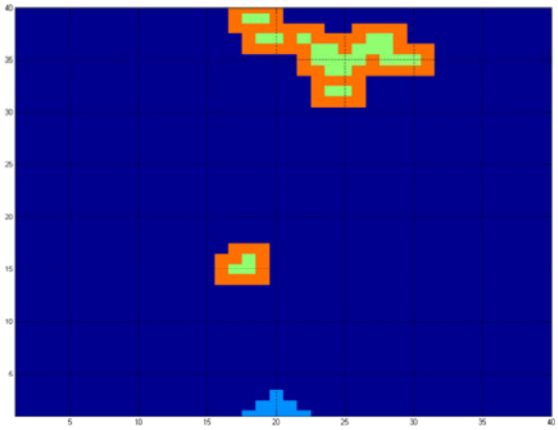


Figure 10: Local grid map representing detected obstacles in scene displayed in Figure 9.

The Figure 11 represents graphically the three regions (violet, orange and azure) for the “Obstacle distance” and three angles (red, azure and violet) for the “Obstacle aperture angle, selected as input variables in the fuzzy controller. The regions are in the same order as they appear in the Figure 4 and Figure 5. In this way a “small” angle is represented by the “red” angle in the Figure 11.

Depending on the “Obstacle aperture angle” and the “Obstacle distance” to the detected obstacle in the local grid map, the “Wheel angle” response will be different.

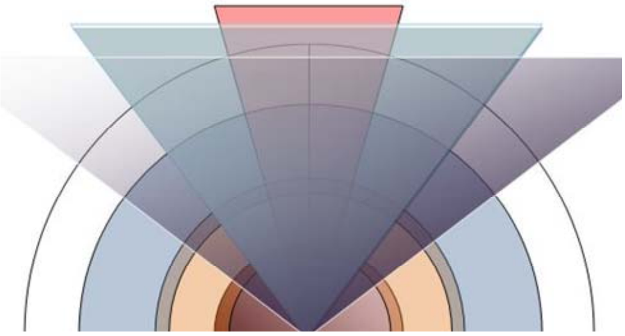


Figure 11: Obstacle detection regions.

The laser range finder has been configured to detect obstacles to a distance of 8 meters. This depth value allows the activation of the fuzzy steering controller in the AVOID agent, generating a deviation trajectory from the obstacle.

The Figure 12 displays three results of the operation of the fuzzy steering controller within the AVOID agent. The first experiment, Figure 12a, shows a person in front of the path of the robot-tractor. In this case, once the person is detected, the AVOID agent is activated and the fuzzy controller generates a deviation trajectory around the person. The Figures 12b and 12c display two experiments where the AVOID agent is activated to deviate the tractor from the tree that appears close to its path.

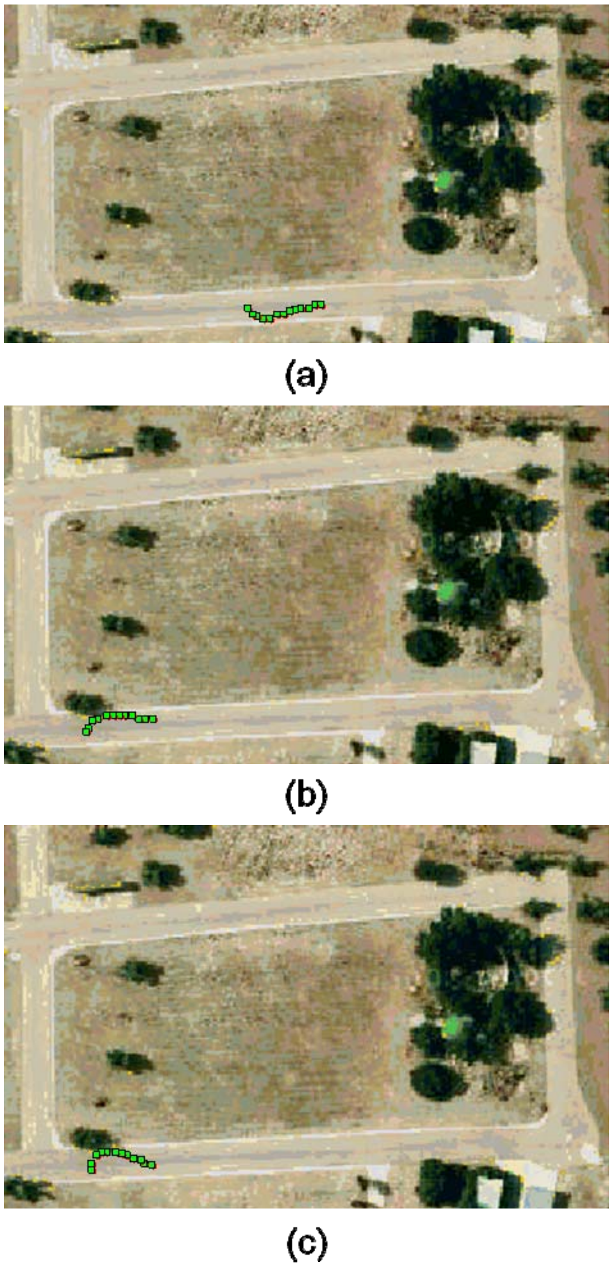


Figure 12: Three scenes of activation of the AVOID agent fuzzy controller.

In these scenes, the robot-tractor was initially controlled by the ADVANCE agent, and upon detection of an obstacle closer than the safety distance, the AVOID agent is activated, by the coordination agent WANDER.

6 COMMENTS AND CONCLUSIONS

The fuzzy controller here developed is a non-analytic-model, based on a set of rules formulated by the expert, to adequately accomplish the obstacle avoidance strategies in an unmanned hydraulic tractor.

This fuzzy control system has been implemented and validated under different ground conditions, both in rough and flat terrains. In all of them, it has achieved the requirements imposed on both speed to reach a reference and low oscillation level.

The human-machine interface, developed in Matlab using a GUI, has been designed and implemented to visualize the environment while the tractor is guided by the WANDER agent of behaviour.

Obstacles depth images, derived from laser range finders, conveniently integrated with domain knowledge results in smart strategies for reactive tractor self-piloting. Intelligent and safe piloting strategies are fundamental issues in the development of unmanned navigation of vehicles in outdoor scenarios.

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