MOBILE ROBOTS
A STUDY ON SENSING AND PERCEPTION SYSTEMS

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Abstract. *Sensors traditionally used in mobile robotics provide raw data. Most of this data is processed and converted into information. This thesis aimed to study traditional sensing techniques using RGB and 3D sensors and propose a new sensing approach embedded in compact hardware, named the DeepSpatial sensor. To reach the goal, a study of point cloud processing in land robots and air flights was carried out, and later the hardware and software architecture was proposed for a new sensing approach. The thesis consists of 4 papers published in journals, where each chapter presents the summary of each published paper.*

Este trabalho é um resumo da tese *"Mobile robots: a study on sensing and perception systems"* apresentada ao Programa de Pós-Graduação em Engenharia Elétrica e Informática Industrial (CPGEI) da Universidade Tecnológica Federal do Paraná, no dia 18 de janeiro de 2021. A tese completa pode ser acessada em https://repositorio.utfpr.edu.br/jspui/handle/1/2860. A tese é composta por coletânea de artigos, composta por 4 trabalhos publicados em periódicos especializados, sendo eles: (1) *Intelligent environment recognition and prediction for NDT inspection*, publicado em *Journal of Intelligent & Robotic Systems*, DOI: https://doi.org/10.1007/s10846-017-0764-6. (2) *A Quadral-Fuzzy Control Approach to Flight Formation by a Fleet of UnmannedAerial Vehicles*, publicado em *IEEE ACCESS*, DOI: https://doi.org/10.1109/ACCESS.2020.2985032. (3) *Intelligent 3D Perception System for Semantic Description and Dynamic Interaction*, publicado em *Sensors*, DOI: https://doi.org/10.3390/s19173764 . (4) *DeepSpatial: Intelligent Spatial Sensor to Perception of Things*, publicado em *IEEE Sensors*, DOI: 10.1109/JSEN.2020.3035355. Além destes trabalhos, a tese teve como resultados parciais trabalhos publicados em congressos e capítulos de livros.

1. Introduction

Mobile robotics is an area of science that studies the development of complex robotic systems, which can freely move in the environment [Nehmzow 2012, Cao et al. 1997]. Unlike a fixed robot, such as robotic arms used in factories [Hayati 1986], a mobile robot can move around in the environment, whether by land, water, and sky [Tan et al. 2017, Ryll et al. 2017, Parker et al. 2016] (Fig. 1).

To perceive the environment, mobile robots can make use of different types of sensors. With the use of LiDAR sensors, it is possible to perform safe naviga-

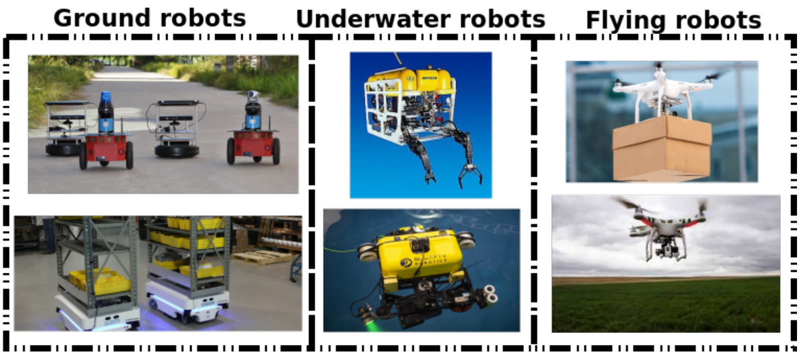

Figure 1. Examples of mobile robots.
Source: Own authorship.

tion by stopping when identifying an obstacle, for example. In addition to 2D sensors, there is another category of sensors capable of providing a higher amount of information. These are 3D sensors. 3D sensors provide data known as PointCloud [Boulch et al. 2017, Rusu and Cousins 2011]. These data are matrices containing the 3D coordinates of each point. They can be collected in two ways, whether by time of flight [Hagebeuker and Marketing 2007], which is the case with ultrasonic sensors, for example, or by structured light [Rocchini et al. 2001] being the most common and cheapest of the techniques. Usually, 3D sensors also provide colors associated with the 3D point; these data are known as RGB-D. This data can be used for various mobile robotics tasks, such as building 3D maps, performing object detection, and other activities [Huang et al. 2017, Giordano et al. 2016]. A visual representation of the sensors mentioned can be seen in Fig. 2.

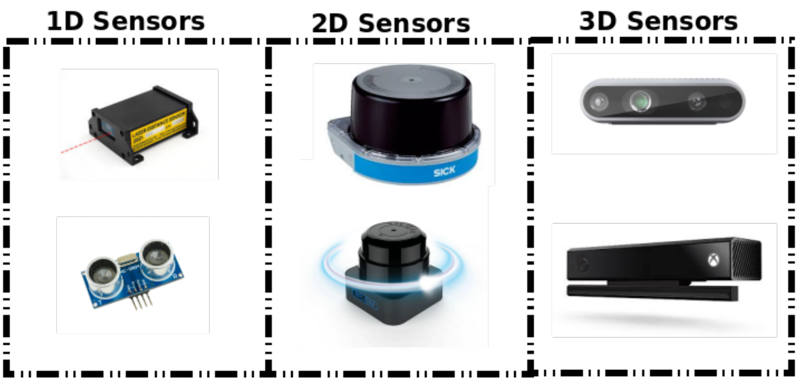

Figure 2. Visual representation of sensors used in mobile robotics.
Source: Own authorship.

In this way, sensors are essential for robotic applications because it is impossible to perform simple tasks such as navigating the environment without them. However, they are designed to provide raw data, which in some cases is not sufficient. Several papers focus on converting sensor data into information, for example, in [Liang et al. 2018, Wang et al. 2018]. However, these papers are not aimed at robotic applications and are usually performed on computers with high processing power.

This thesis aims to study and analyze the use of sensors in mobile robots to propose contributions in sensing techniques, mainly processing data provided by traditional sensors into information used by the robot. Intelligent sensors combine physical sensing with data processing techniques to generate intelligent information, which can be used for the robot to obtain information from the environment. A study of sensors was first carried out on terrestrial robots, where the limitations of traditional sensors were verified. Most sensors provide the same type of data, point cloud. Subsequently, converting point cloud data into useful information was carried out in a study with drones. After the preliminary studies with the sensors, an intelligent sensing approach was proposed, using deep learning techniques. Finally, a sensor architecture was proposed, where all the developed technique is embedded in a single equipment. Validations were made at all stages of the thesis.

2. Objective

This thesis proposes a study, analysis, and new approach to environmental sensing. The main focus is to expand the sensors' information, transforming the measured data into useful information. This new technique of perception of the environment will allow robots to safely navigate the environment, knowing which objects are around them, making the robot capable of performing specific actions for each object. This technique must be embedded in hardware that is robust enough to perform all robot actions independently. Therefore, this thesis's general objective is to develop an intelligent sensor capable of identifying dynamic and static objects, extracting characteristics from the identified objects, and when coupled to a robot, interact with it to support an autonomous decision-making capacity by part of the robot.

2.1. Specific objectives

In order to achieve the main objective, the following specific objectives are outlined.

1. Develop a study and analysis of sensing techniques for mobile robots, using the manipulation of point cloud data provided by different sensors, for the creation of maps, object identification, and navigation in order to understand the use of traditional sensors applied to mobile robotics and identify possible improvements;
2. Apply point cloud techniques in aerial robot problems in order to validate sensing techniques. Aerial robots share the same sensing needs as terrestrial robots. This study aims to validate the data manipulation approach for generating information for the robot;
3. Propose a 3D perception system from the data processing of traditional sensors. The proposed system must be able to generate information such as the three-dimensional position of objects in the environment around the sensor and identify objects using computer vision techniques in RGB images;
4. Develop an approach to solving the egomotion problem so that intelligent sensing techniques can identify movements. In addition, it is expected to embark the entire approach proposed in a compact equipment, coupled to a mobile robot;

3. Contextualization

This section aims to contextualize the papers attached to this thesis with the theme of studies, which is "*Mobile robotics: Perception of the environment*". In addition to bringing a contextualization of the works with the research area, a brief comparative theoretical framework will present the works developed and the state of the art. The specific theoretical review of each work is presented in its respective section.

With this thesis's focus on the study of sensors for use in mobile robots, the general objective was divided into four specific objectives. In the first specific objective, the work [Teixeira et al. 2018] was developed, while in the second specific objective, the result was the work [Teixeira et al. 2020]. For the third specific objective, the work [Teixeira et al. 2019] was developed. The fourth specific objective is presented in the section 7. Figure 3 presents an illustration of the works attached to this thesis. It is worth mentioning that some works were developed for congresses and book chapters and are not attached to this thesis.

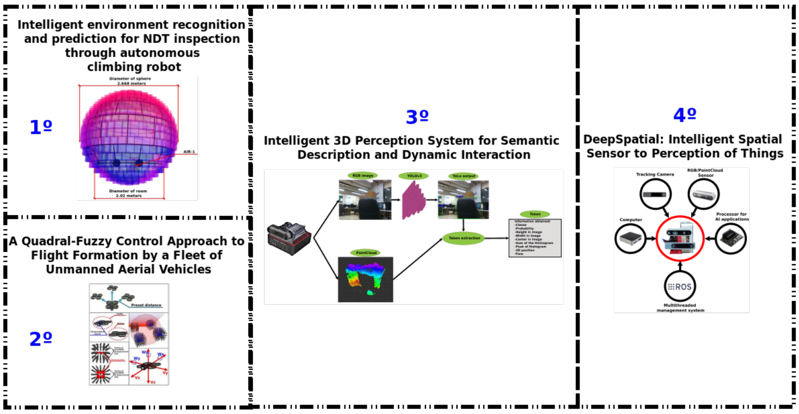

Figure 3. Division of the works presented in this thesis by specific objectives proposed.

In the section 4, the work "*INTELLIGENT ENVIRONMENT RECOGNITION AND PREDICTION FOR NDT INSPECTION THROUGH AUTONOMOUS CLIMBING ROBOT*" [Teixeira et al. 2018] was developed. This work aimed to develop a mapping strategy for an inspection robot for liquefied petroleum gas (LPG) tanks. LPG tanks are spherical tanks that require periodic inspections. In this work, Fuzzy control techniques and the use of multiple 3D sensors were used to create a mapping strategy. An environment prediction strategy was developed, based on data obtained by the sensor and knowledge inference about the inspection environment. For the prediction, artificial neural networks were used to infer a certain percentage of the predicted points.

Still, with the focus of understanding the sensors and improving the sensing techniques in mobile robotics, in the section 5 the work "*A QUADRAL-FUZZY CONTROL APPROACH TO FLIGHT FORMATION BY A FLEET OF UNMANNED AERIAL VEHICLES*" is presented [Teixeira et al. 2020]. This paper consists of a new proposal for navigation in formation with multiple drones. If Drones fly in formation, they can perform collaborative tasks, such as cargo transportation. The work used intelligent control techniques, such as the use of a Fuzzy system. The information was shared from the leading Drone to the worker Drones, who together performed an obstacle avoidance action maintaining the formation.

From these works, it became clear the need for a robot to identify objects and their positions. This work used the identification of the weld bead and its junctions to predict the entire environment. With the results obtained in the papers [Teixeira et al. 2018] and

[Teixeira et al. 2020], the next work of this thesis aimed to develop a sensing strategy, not focusing on the robot, but in generating information from traditional sensors. The work "*INTELLIGENT 3D PERCEPTION SYSTEM FOR SEMANTIC DESCRIPTION AND DYNAMIC INTERACTION*" [Teixeira et al. 2019] was developed, where it aimed to develop a new environment perception strategy, using computer vision and sensing techniques.

In this thesis, computer vision techniques were used to identify objects in an RGB image. Related works can be seen at [Liu et al. 2020, Zhao et al. 2019, Hu et al. 2018], where deep learning concepts are used to recognize objects in traditional images. For object recognition, YoLo [Redmon and Farhadi 2018, Redmon and Farhadi 2017] was used, as it has a good ratio between performance and accuracy. The data obtained by YoLo are processed with the 3D perception sensors to identify the object's position. Related works can be found at [Simony et al. 2018, Simon et al. 2019, Yang et al. 2018], where computer vision techniques were used together with 3D perception data to identify objects. Unlike the works cited, the work present in this thesis, in addition to identifying objects in the real world, performed the tracking calculating speed, direction, and acceleration.

Section 6 results in a sensing strategy, in which objects in the environment and their 3D positions are identified and calculating their speeds, direction, and accelerations. However, the strategy was developed on a fixed computer and cannot be coupled onto the robot. From here, the work presented in the section 7 under the name "*DEEPSPATIAL: INTELLIGENT SPATIAL SENSOR TO PERCEPTION OF THINGS*" [Teixeira et al. 2021] was developed, where the objective is to improve the techniques developed and embed them on portable equipment and attach it to the robot, thus fulfilling the third specific objective proposed by this thesis. In this work, the robot movement in the environment was considered.

The proposed sensor, DeepSpatial, identifies objects in the environment and their 3D position, tracking them and calculating their speed and direction, compensating for their movements in the environment using visual odometry, and can be embedded onto the robot.

4. Intelligent environment recognition and prediction for NDT inspection through autonomous climbing robot

This section presents the article published in the *Journal of Intelligent & Robotic Systems* (ISSN: 0921-0296). The data of the paper is shown in Table 1.

This study's motivation is the difficulty in carrying out inspections in storage tanks for liquefied petroleum gas (LPG). Inspections are carried out by people who need to put themselves in situations that are often dangerous to their health, such as in high places or an environment with a high concentration of gases harmful to the human body. In this way, the project aims to avoid exposing people to risk. A mobile robot is proposed under development by the Federal University of Technology – Paraná in partnership with Petrobras. The creation of the mobile inspection robot, called *Autonomous inspection robotis* currently has three versions. This work uses version 1, called AIR1.

To be able to inspect an LPG storage tank by a robot autonomously and intelligently, the equipment needs to be able to collect data from the environment, analyze and process them, and make decisions. This work focuses on processing data from different

Table 1. Data of the paper *Intelligent environment recognition and prediction for NDT inspection through autonomous climbing robot. Source: Own authorship.*

Authors	Teixeira, M.A.S.; Santos, H.B.; de Oliveira, A.S.; Arruda, L.V.R.; Neves-Jr, F.
Title	*Intelligent environment recognition and prediction for NDT inspection through autonomous climbing robot*
Journal	*Journal of Intelligent & Robotic Systems*
ISSN	0921-0296
DOI	https://doi.org/10.1007/s10846-017-0764-6
Publication date	January 19, 2018 online and October 2018 printed

sensors to create and predict the map of the environment. This map is also possible to carry out the trajectory planning, which would be the path to be taken by the robot during the inspection. Defining trajectory planning is not the focus of this work. The main objective is to create a three-dimensional representation of the environment, with as many features as possible, without going through the entire environment. The goal is achieved with the use of artificial intelligence techniques, knowledge inference, raw sensor data processing, among others.

This work concludes the first specific objective of the thesis, contributing to identifying possible improvements and contributions in the area of data processing from sensors used in robots.

5. A Quadral-Fuzzy Control Approach to Flight Formation by a Fleet of Unmanned Aerial Vehicles

This section presents the paper published in the *IEEE Access* journal (ISSN: 2169-3536). The data of the paper is shown in Table 2.

Table 2. Data of the paper ***A Quadral-Fuzzy Control Approach to Flight Formation by a Fleet of Unmanned Aerial Vehicle.*** Source: Own authorship.

Authors	TEIXEIRA, Marco Antonio Simoes; NEVES-, FLAVIO ; KOUBAA, ANIS; DE ARRUDA, LUCIA VALERIA RAMOS ; DE OLIVEIRA, ANDRE SCHNEIDER
Title	*A Quadral-Fuzzy Control Approach to FlightFormation by a Fleet of UnmannedAerial Vehicles*
Journal	*IEEE ACCESS*
ISSN	2169-3536
DOI	https://doi.org/10.1109/ACCESS.2020.2985032
Publication date	April 2, 2020

This work is motivated by tasks that need to be performed by multiple agents (drones). Some tasks, such as transporting heavy loads, monitoring, exploring environments, sensing, among others, in many cases need to be carried out separately by different agents. When the task is performed by a single agent/robot, such as cargo transportation, the action is limited by the robot's carrying capacity. When executed by more agents, the maximum weight of the product transported can be increased, increasing the number of agents involved in the task.

This work aims to carry out a navigation approach in formation for multiple drones. To perform collaborative tasks, the first step to be taken is an approach to navigate the environment without colliding, maintaining a pre-defined formation. This paper is concerned with the approach of navigation and high preservation of agents. This work does not focus on odometry errors, considered non-existent here.

This paper fulfills the second specific objective of the thesis by proposing the use of 3D perception sensors in aerial robots (drones). In addition to using 3D sensors for navigation and obstacle avoidance actions, an approach was proposed where only one agent can perceive the environment and share the information already processed with the other agents. Therefore, each agent does not need to have a sensor attached to it. This paper is open access under the Creative Commons Attribution 4.0 license and can be attached to that thesis.

6. Intelligent 3D perception system for semantic description and dynamic interaction

This section presents the paper published in the *Sensors* journal (ISSN: 1424-8220). The data of the paper is shown in Table 3.

Table 3. Data of the paper *Intelligent 3D perception system for semantic description and dynamic interaction.* Source: Own authorship.

Authors	Teixeira, M.A.S.; Nogueira, R.C.M.; Dalmedico, N.; Santos, H.B.; Arruda, L.V.R.; Neves-Jr, F.; Pipa, D.R.; Ramos, J.E.; Oliveira, A.S.
Title	*Intelligent 3D Perception System for Semantic Description and Dynamic Interaction*
Journal	*Sensors*
ISSN	1424-8220
DOI	https://doi.org/10.3390/s19173764
Publication date	August 30, 2019

This paper's motivation is that the data from the traditional sensors used in mobile robots, in most cases, are not enough for decision making, requiring the processing and fusion of sensors. For example, to know an object's position in a 3D environment, it is necessary to recognize the object in an image and then merge it with the depth data.

It is worth mentioning that the sensors fulfill the function for which they designed, providing raw data, but the data needs to be processed to generate information. Thus, this paper aims to propose a new sensing approach, where the data provided by the sensors will be processed, and useful information will be returned for the robot to use for decision making.

Regarding the theme of this thesis, this paper fulfills the third specific objective. The approach proposed in this paper was developed based on the sensing problems found in sections 3 and 4, where studies of traditional sensing techniques were carried out. This article is open access under the Creative Commons Attribution license and can be attached to that thesis.

7. DeepSpatial: Intelligent Spatial Sensor to Perception of Things

This section presents the paper published in the *IEEE Sensors* journal (ISSN: 1558-1748). The data of the paper is shown in Table 4.

Table 4. Data of the paper *DeepSpatial: Intelligent Spatial Sensor to Perception of Things.* Source: Own authorship.

Authors	TEIXEIRA, Marco Antonio Simoes; NEVES-, FLAVIO ; KOUBAA, ANIS; DE ARRUDA, LUCIA VALERIA RAMOS ; DE OLIVEIRA, ANDRE SCHNEIDER
Title	*DeepSpatial: Intelligent Spatial Sensor to Perception of Things*
Journal	*IEEE Sensors*
ISSN	1558-1748
DOI	10.1109/JSEN.2020.3035355
Publication date	04 November 2020

The paper presented in section 5 showed good results validating the proposed strategy but left some problems open that need to be improved to be coupled to the robot. It is possible to mention two main problems, egomotion, and the need to embark the entire approach in a compact device so that it can be attached to the robot.

Thus, this paper aims to solve the egomotion problem, create compact equipment capable of executing the proposed approach, couple the equipment to the robot, and perform real experiments. The proposed equipment consists of an Intel Nuc NUC5i5RYH minicomputer, Nvidia Jetson Nano and the Intel RealSense D435i and Intel RealSense Tracking Camera T265 sensors. The Intel Nuc NUC5i5RYH and Nvidia Jetson Nano equipment's main configurations can be seen in the Table 5.

Table 5. Components used in the development of the paper *DeepSpatial: Intelligent Spatial Sensor to Perception of Things.* Source: Own authorship.

Component	Description	Specification
Intel Nuc NUC5i5RYH		
CPU	Intel® Core™ i5-5250U	Cores: 2, Threads: 4, Frequency: 1.60 GHz
RAM memory	DDR3L-1600 1.35V SO-DIMM	8 gb
Nvidia Jetson Nano		
CPU	ARM® A57	Cores: 4, Frequency: 1.43 GHz
GPU	NVIDIA Maxwell	128-core
RAM memory	64-bit LPDDR4 25.6 GB/s	2 gb

This paper fulfills this thesis's last specific objective, validating the new approach proposed in real experiments. As a result, the approach was embedded in compact equipment, and the equipment was coupled to the robot.

8. Conclusion and Future Work

This thesis proposes a new sensing approach for mobile robots. Mobile robots need to see the environment around them to make decisions, such as avoiding obstacles. The sensors can also be used to develop mapping techniques, object identification, inspection, and many other activities. This thesis aimed to improve the data coming from traditional RGB-D sensors, which are images with a notion of depth, in order to develop a device capable of identifying objects and tracking them, they can be used by the robot for making the decisions. The thesis is written in the format of a collection of articles, thus, some sections of the thesis are articles already published in journals.

Section 1 presents the problem of this thesis, with a brief description of mobile robots' need to perceive the environment around them. The general and specific objectives of the thesis were also presented. Section 3 presented a contextualization of the thesis, comparing the works developed with related works in the literature and associating each work with the general and specific objectives proposed.

Section 4 presents the work *Intelligent environment recognition and prediction for NDT inspection through autonomous climbing robot* [Teixeira et al. 2018], where a strategy for mapping Liquefied Petroleum Gas (LPG) storage tanks to a mobile inspection robot was developed. For the preparation of the map, knowledge of the inspection environment was inferred, such as the spacing between the weld beads. In this way, it was possible to predict the entire structure, by identifying parts of the tank, such as weld junctions. This work made use of several sources of perception, being 1D, 2D, and 3D. In this way, this work explored to the maximum of the use of traditional perception sensors, making evident the need for improvement in this area.

Section 5 presents the work *A Quadral-Fuzzy Control Approach to Flight Formation by a Fleet of Unmanned Aerial Vehicles* [Teixeira et al. 2020] where a drone formation strategy was proposed. The strategy aims to carry out the flight while maintaining a specific formation between 4 drones so that they can perform collaborative tasks, such as cargo transportation. The work uses a single RGB-D sensor to detect obstacles, and Fuzzy controllers to perform obstacle avoidance and position control. This work fulfills the second specific objective of the thesis, where point cloud processing techniques are applied in aerial robots so that the sensing techniques can be validated not only in terrestrial robots but also in aerial robots.

The strategy presented in the section 4 and 5 made use of several traditional sensors in mobile robotics, showing the need for innovation in this area. In this way, the work presented in the section 6 [Teixeira et al. 2019] was developed. Section 6 presents the work *Intelligent 3D Perception System for Semantic Description, and Dynamic Interaction* [Teixeira et al. 2019], where a new sensing strategy is proposed. In this work, a new approach to sensing from traditional sources of perception is proposed. In this way, the RGB-D perception sensor is used to generate new types of information, such as identifying objects in the environment and their spatial positions. It is used for object identification, computer vision techniques; in this work, the YoLo algorithm was used.

This section fulfilled the third specific objective of the thesis, focusing on elaborating a new sensing proposal.

Section 7 presents the work *DeepSpatial: Intelligent Spatial Sensor to Perception of Things* [Teixeira et al. 2021], an improvement on the previous work, where the proposed strategy is embedded in a compact equipment that can be attached to the mobile robot. The proposed sensor comprises several pieces of equipment: a computer (an Nvidia Jetson board to perform the graphic processing), an RGB-D camera, and a camera to perform the visual odometry. With visual odometry, it is possible to calculate the robot's displacement in the environment and compensate for this displacement in the identified objects' position. As a result, the equipment proved to be capable of executing the technique without using much CPU processing, about 53.4 %. This work fulfilled the thesis's objective to develop a new source of perception for mobile robots, where intelligent information is provided, not just depth data.

This thesis addressed the study of sources of perception in mobile robots, starting with a preliminary study on traditional sensing strategies, such as the use of sensors to avoid obstacles and map obstacles, ending with the proposal of a new source of perception of the environment, proposing a new sensor capable of identifying objects and their spatial position, in addition to predicting their displacement in the environment. In this way, this thesis carried out a study on sensing techniques for mobile robots, elaborated a proposal for a new sensing approach, and developed and validated the strategy on embedded hardware, leading the author to browse through several science areas.

It is noteworthy that during the development of the thesis, some hardware and software limitations were encountered. Regarding the hardware, a big problem is the processing capacity, being necessary to use two different computers, one for the processing of the algorithm as a whole, and the other for the processing of computer vision techniques, such as YoLo. The thesis aimed to convert sensor data into information in terms of software, and there are few similar solutions. A suggestion for improvement would be the replacement of YoLo by recent object recognition strategies, such as the *Mediapipe*. This replacement could result from the deletion of one of the computers, as *Mediapipe* consumes less processing than YoLo. Below are some suggestions for future work.

8.1. FUTURE WORK

Based on the studies developed in this thesis, it was possible to identify some points that can be improved in the future, both about the works presented here, as well as new works to be developed. Future works are presented in the list below.

1. Adding cargo to the flew in formation with Drones, and experiments in real environments. The work showed that it is possible to carry out cargo transport with multiple drones. However, the effect of cargo on the flight was not discussed. Real experiments need to be done to validate the strategy in a real environment;
2. Enhancement of the DeepSpatial sensor to be used in the inspection environment. The sensor currently identifies only objects through the YoLo network. To use the sensor in the inspection environment, the sensor can be adapted to identify critical environmental components, such as tubes and weld beads. This information can be used for location and other inspection actions;

3. The improvement of the object tracking strategy present in the DeepSpatial sensor, in its latest version, the strategy consists of verifying whether the objects belong to the same class, and if they belong, the Euclidean distance between them is calculated. Deep learning tracking algorithms can be used. However, it is necessary to assess whether these techniques do not impair the performance of the sensor;
4. The creation of a semantic map, where the position of the objects identified by the DeepSpatial sensor is used to develop an intelligent mapping strategy. The position of each object will be saved, and its movements will also be calculated continuously if the object is in motion;
5. Use and adapt the sensing techniques developed for mobile robots in other environments, such as industries and smart cities.

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