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CHALLENGES AND OPPORTUNITIES OF ROBOTIZATION IN AGRICULTURAL GREENHOUSES

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Abstract. *The presence of robots in agriculture has grown significantly over the years, overcoming many problems and challenges in this area. This work aims to identify research and development opportunities in automation and robotization of agricultural greenhouses based on the survey of updated state-of-the-art information regarding the application of robots in protected cultivation agriculture. Therefore, it is possible to reconcile the most diverse researches involving robotic applications in greenhouses, such as robot positioning techniques, autonomous navigation methods by algorithms, development of compact harvesting mechanisms, weed control, spraying, irrigation, among other control factors, such as temperature and humidity, making protected cultivation sites totally autonomous, resulting in the well-known "smart greenhouses". This work deals to contribute to the definition of the main project requirements for the automation of protected crops based on the need analysis of functional modules. This article emphasizes and briefly details the robotization systems in existing greenhouses, combining this aspect with the massive demand of the sector, in addition to structuring and systematizing the new opportunities for obtaining a fully autonomous and robotic greenhouse.*

Keywords: *Robotic Greenhouse, Mechanism Analysis, Agriculture Machinery, Smart Greenhouses.*

1. INTRODUCTION

Agriculture can be an opportune sector for the application of automation and robotization such as the industry, so the challenges for robots in agriculture are diverse. However, agricultural environments known as greenhouses or sheltered cultivation, unlike industrial facilities, they are not fully structured and automated. An extremely relevant fact is that, unlike industrial processes, agricultural activities often cannot be divided into functional modules, as they require more complex activity combined with non-simple actions. For all these reasons mentioned, agricultural activities need robust and multifunctional robots (Neves, 2017).

The presence of robotics in agriculture is not an unusual concept, as in protected cultivation environments (greenhouses), this feat has been studied for more than two decades. Several research fronts pursued to assist in activities and operations within the greenhouses, such as robotic mechanisms for soil preparation, planting, harvesting (tomato, pepper, cucumber, strawberry, among others), control of parameters (humidity, temperature, definition and luminosity) and even for irrigation, spraying, pesticide application and weeding (Hackenhaar, 2015).

For Tangerino (2011), the use of robots to aid agricultural activities has an admirable potential as a technological tool for precision agriculture (item discussed in section 3), thus combining numerous theories and methods of numerical and robotic control, already implemented in applications from several other areas, such as the industrial sector.

One of the ways to boost food production is robotics. Recently, numerous advances have been made in the sector, and the speed of operation and manipulation of robots has surpassed humans, conducting various activities uninterruptedly and with minimal maintenance (Tanke et al., 2011).

This work aims to serve as reference for new challenges in future researches and improvements for "smart greenhouses" in terms of hardware and software solutions increasing the efficiency in requirementes control (temperature, humidity, distribution of fertilizers and inputs, pest control) and the speed of planting and harvesting inside the greenhouses, considering that such space is limited and controlled.

Section 2 describes agricultural greenhouses and their constructive aspects, highlighting the main parameters for developing a robotic design, considering the main internal dimensions of the protected cultivation environment, the main models of agricultural greenhouses and their respective cultures, in addition to the description detail of a commonly used business model. The next section covers the main processes and models of automation in state-of-the-art greenhouses,

covering the robot systems already used and new development opportunities. Then, section 4 summarizes the main conclusions and considerations of the state of the art. At last, section 5 presents the references used for the development and structuring of this work.

2. AGRICULTURAL GREENHOUSES

In the last two decades, between the years of 1990 and 2000, the use of agricultural greenhouses quickly expanded its borders around the world. Estimates indicated (in 1990) a total area of 716,000 hectares with greenhouses, but in 2010 this number had exceeded more than 3 million hectares (400%) growth, most of which were destined for the planting of vegetables, with China concentrates the largest portion of protected cultivation area, as shown in Table 1 (Silva et al., 2014).

Table 1. Protected planting growth in two decades.

Ranking	Country	Area (*hectare*) – 1990	Area (*hectare*) – 2010
1	China	600.000	3.346.800
2	Spain	18.500	70.400
3	South Korea	3.807	47.000
4	Japan	24.000	36.000
5	Turkey	9.800	33.496
6	Other countries (total of 84 countries)	60.184	134.319

Despite this, Brazil, having an area of cultivation much lower than the countries that lead the ranking, leads the position when it comes to countries in South America. According to data from COBAPLA (Brazilian Committee for the Development and Application of Plastics in Agriculture), Brazil has some 22 thousand hectares of area under greenhouse cultivation, whose main activities are related to the cultivation of vegetables, nurseries and flowers, and half of this area is concentrated in the state of São Paulo. In these areas of protected planting, pepper, lettuce, cucumber and tomato crops stand out (Silva et al., 2014).

The state of São Paulo is one that uses the most protected planting culture, representing about 50% of the total greenhouses in the country. Next is Santa Catarina, Paraná, Rio Grande do Sul, which together represents 20% approximately. The state of Minas Gerais is responsible for 15% of the total of greenhouses, while the other states are responsible for another 15% (COBAPLA, 2016).

When it comes to the area covered by greenhouses, it can be Almería, a region of Spain known for its considerable greenhouses, which cover more than 30.000 hectares of land from the sea to the mountains. Greenhouses represent around 3% of the land in the Spanish province, which accounts for 40% of all Spanish vegetable exports. There are more than 2.700.000 metric tons of cultivated products, including cucumbers, lettuce, beans, watermelon, among others. What makes these numbers more surprising is that 8% of all greenhouses concentrated on the aforementioned region use hydroponic methods, which correspond to 54% of the entire hydroponic industry in Almería. This region is known as the "Sea of Plastic", precisely because the agricultural effluents are covered by special plastics, as shown in Figure 1 (Jacques, 2016).

Figure 1. Aerial view satellite image of agricultural greenhouses in the Spanish province (adapted from MagnusMundi, 2016).

2.1 Main models of agricultural greenhouses

According to Souza (2014), "agricultural greenhouses are structures where several varieties of crops are grown in an environment protected from bad weather, whose main objective is to provide plants with conditions close to the ideals for their development".

This work presented a focus on professional greenhouses, produced by large world industries and not in small amateur greenhouses, that is, that whose structures are made of wood and the like.

The differences between each model are basically related to the structure of the support arches and their various shapes (Figure 2). The main types are (Maxiaço, 2021): Lattice arch (Figure 2.a), Sawtooth arch (Figure 2.b), Tubular arch (Figure 2.c).
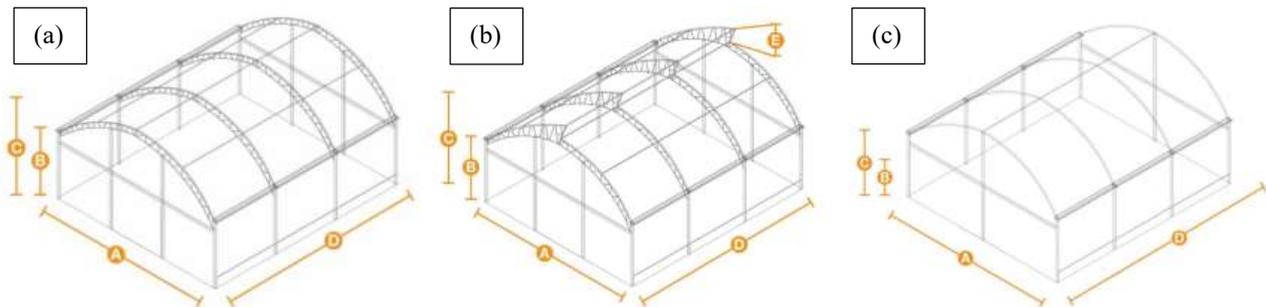

Figure 2. Main models of agricultural greenhouses. Lattice arch greenhouse (a); sawtooth arch greenhouse (b); tubular arch (c) (adapted from Maxiaço, 2021).

2.2 Constructive aspects

From an analysis of the abovementioned, it was found that the model commonly used commercially corresponds to the tubular arch structure. Thus, the constructive parameters were determined, according to Table 2, which serves as the basis for a future robotization project, since one of the objectives of this work is precisely to determine a dimensional pattern for constructing of a robotic greenhouse and autonomous. The geometric dimensions indicated by the letters "A, B, C. D" in the table below are indicated in Figure 2.

Table 2. Main dimensions of the tubular arch greenhouse.

A – Width (m)	B – Ceiling Height (m)	C – Total Height (m)	D – Length (m)
6.50	3.00	4.50	30.00
7.00	3.50	5.00	30.00
8.00	4.00	5.50	30.00
9.50	4.50	6.00	30.00
10.00	5.00	6.50	30.00
11.00	5.50	7.00	60.00
12.50	5.50	7.00	60.00
14.00	5.50	7.00	60.00
15.00	5.50	7.00	60.00

Another aspect to be analyzed is the dimensions of the benches for growing crops used in the protected environment. Thus, it is possible to establish one more parameter for the design of a robotic greenhouse.

It is extremely important to determine the dimensions of the agricultural benches, as this way it is possible to define the total course of translation of the gantry robot along the axes of the Cartesian references, as well as its work area, with the end effector being a robotic gripper or even a spray nozzle (as shown in Figure 7 in section 3.3).

According to table 2, the system must be dimensioned allow to the dimensions of the width of the greenhouse (A) and its respective height (B), precisely because the Gantry mechanism performs the activities suspended on the agricultural benches using the greenhouse structure itself for its coupling and support (Figure 3.a).

To determine the measures, a field research was carried out analyzing the main agricultural greenhouses used in the protected cultivation of various cultures, such as strawberries, vegetables, seedlings and flowers. Therefore, the dimensions most commonly found inside greenhouses in relation to the spacing of benches and aisles are shown in Figure 3.b:
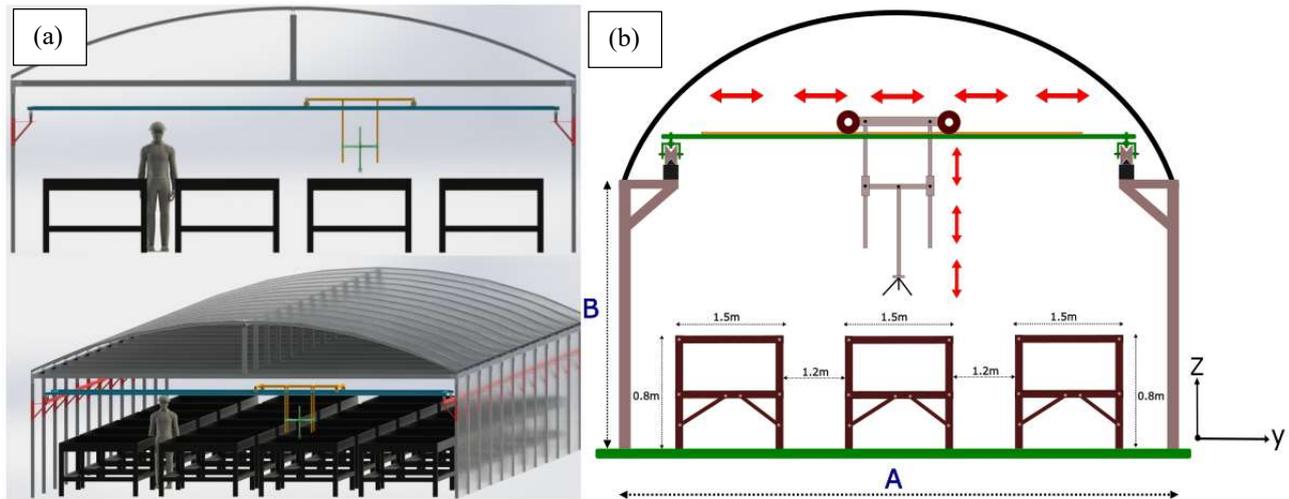
Figure 3. Robotic system workspace of Gantry mechanism as a opportunity low-cost robotization solution.

3. ROBOTICS IN AGRICULTURE

The use of robotic machines and systems in agriculture has experienced a significant gain in investment and research in recent decades, due to the use of application robotics and automation to perform tasks, including precision agriculture, which is about control, guidance and operation of autonomous equipment to perform agricultural activities (Auat and Carelli, 2013).

According to Amer et al. (2015), the presence of robotics in agriculture is not a new concept, and its history began more than 20 years ago with research into cherry, cucumber and tomato harvesters. However, the first robot intended for agricultural applications was developed only in 1998 by Astrand and Baerveld to control weeds. In 2004, Bak and Jakobsen designed a robotic mechanism that moved between crop planting lines, locating weeds using a camera and a GPS receiver. In the same year, Hofstee, Grift and Tian developed a machine vision algorithm, with autonomous orientation (Auat and Carelli, 2013).

Batista (2016), developed a Gantry-type robot for agricultural greenhouses with 3 degrees of freedom (DoF) with the irrigation function for a given crop. In 2007, Starcevic designed a drying robot for protected cultivation with the objective of removing sludge from plants, thus increasing their calorific value (Porsch et al., 2019).

3.1 Precision agriculture

Precision agriculture is one of the ways of agricultural management of crop production stages, thus allowing a modular application and integration of the most varied innovative technologies, as long as the variability of the determining productive factors is known (Valdiero et al., 2015).

The disorderly use of natural resources has caused numerous environmental problems and limited agricultural production capacity. Precision agriculture has become one of the main tools in this sector, to have a rational, controlled and optimized use of these resources. The vital challenges involving this theme are related to the conservation of the environment and production sustainability, so some aspects are essential, such as maintenance of soil fertility, pest and disease control and the correct use of water resources (Tschiedel and Ferreira, 2002).

Thus, it is necessary to use tools that help in the decision-making process, transforming data into relevant information. One of the ways to achieve an increase in agricultural productivity and quality is the controlled and precise application of inputs, resulting in an adequate preparation of the soil with its homogeneous properties and attributes according to the requirements of the culture grown in it. (Tschiedel and Ferreira, 2002).

Despite this, research related to precision agriculture in Brazil only occurred from the 1990s onwards, with the use of GPS devices and computer programs that helped to obtain georeferenced data (Resende et al., 2016).

3.2 Greenhouse robotization

Cultivation in agricultural greenhouses (protected cultivation) without proper monitoring, arising from numerous climatic factors, makes it impossible for the farmer to obtain adequate production of certain foods. The agricultural sector is one of the areas that still require the help of labor in its production stages, whether in planting, harvesting or other cultural care in the field. Thus, there are numerous challenges similar to the shortage of labor for agribusiness activities.

Despite the agricultural scenario is beginning to undergo changes due to mechanization and automation in the field. Automated equipment makes up for the lack of human resources, conducting the most varied activities that once required

countless people. However, these changes caused by this mechanization process boosted the production of the most varied crops, reduced losses, in addition to allowing new possibilities and innovation fronts for agribusiness (Venturus, 2021).

Several activities that went through a mechanization process significantly improved the efficiency of processes in the field and agribusiness, such as the mechanized harvesting of strawberries and tomatoes in greenhouses, using autonomous robots and robotic claws to accomplish this feat.

3.3 Gantry robot

One of the variations of a Cartesian robot (Figure 4.a) is called Gantry (Figure 4.b and 4.b.1), resulting in a movement with 3 translations, whose movement axes are coincident with a Cartesian reference coordinate system. This structure is generally used in pick-and-place operations, whose main advantage is the agility of operation with larger and heavy objects (Romano, 2002). For Sciliano et al. (2009), a Cartesian robot is composed of three prismatic joints that provide ease of positioning the end effector. According to Rosário (2005), this robot model stands out for their high degree of mechanical rigidity (prismatic joint) and the precision in the position of the actuators.
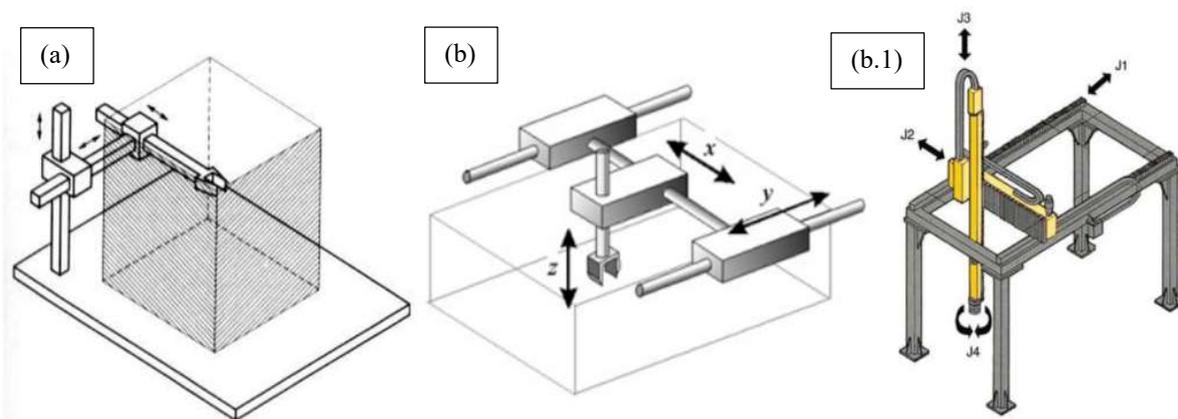

Figure 4. Cartesian robot (a); Gantry robot (b) (adapted from Porsch et al., 2019; Paatz, 2008).

The need for producers to protect their crops, especially during the most divergent climatic periods is the most relevant factor for increasing productivity, resulting in a greater number of harvests per year, thus improving the quality and quantity of products, regardless of climate variations (Souza et al., 2015).

Figure 5.a show a multifunctional irrigation robot, called RIRRIG, developed by Batista (2016), 3 degrees of freedom with an electrical drive to carry out irrigation and a given crop. One of the main impacting points provided by automating of agricultural management is the reduction of intense and repetitive work activities, which has a positive social impact, filling the shortage of labor in addition to greater care for the physical health of rural workers. However, this robotic project does not use the greenhouse structure as a form of support for the portico, that is, it is a structure uncoupled from the greenhouse. Figure 5.b and 5.b.1 shows the design of a Gantry-type robot developed by Porsch et al. (2019) for agricultural applications in greenhouses, such as planting and harvesting vegetables. In summary, Cartesian and Gantry-type robots are used to: irrigation, pulverization, localized application of fertilizers and pesticides and weeding.
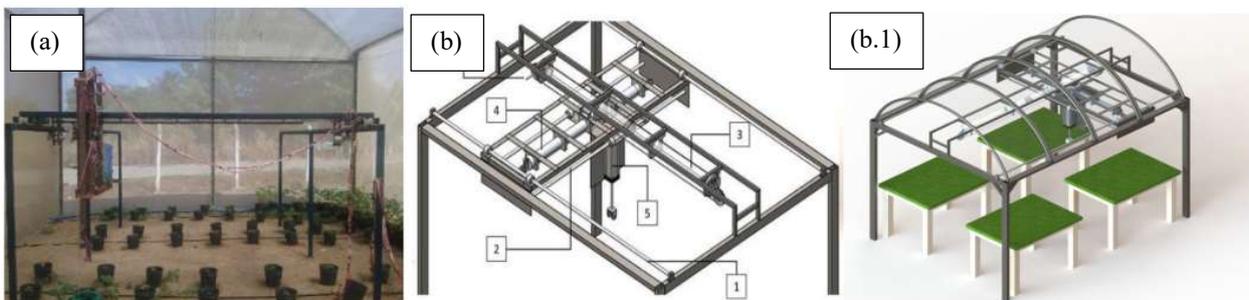

Figure 5. RIRRIG Robot (a); Gantry robot for growing vegetables (b) (adapted from Porsch et al., 2019).

On the other hand, Figure 6 is a "farmer robot", so called, or also labeled FARMBOT, which in turn, does not use the greenhouse structure for its coupling. The user chooses which vegetable to plant, selects the seeds and the robot do the automated planting, in addition to the exact irrigation of water that each plant needs, ensuring correct growth. Thus,

the software defines the distance between the plants' feet so that no problems occur during their development, in addition to detecting weeds that have grown together with the plants.

Figure 6. FARMBOT robots (adapted from Farmbot, 2021).

Additionally, the mechanism in question offers multifunctionality, being able to meet the most diverse operations for the care of a protected crop, as the end effector can be changed according to the needs of the cultivated crop. The system has more than six types of multifunctional heads, which are they (Farmbot, 2021):

- Rotative Tool: responsible for weeding, drilling and soil-turning operations (Figure 7.a);
- Irrigation Nozzle: with a solenoid valve, this tool allows you to water with precision using a gentle sprinkler, thus allowing personalized and controlled irrigation according to each cultivated crop (Figure 7.b);
- Weeding Claw: responsible for weeding, mainly in removing agents that hinder the correct development of plants (Figure 7.c);
- Soil Sensor: by measuring the soil moisture content at each cropping site, this tool allows you to irrigate crops more efficiently, and it can also measure the soil temperature to detect the risk of failure in germination (Figure e.d)
- Camera: with the objective of recording photos of plants and soil, in addition to detecting weeds and pests, even classifying the fruits according to their ripeness based on an analysis of the tonality of their surface (Figure 7.e);
- Injector nozzle: the main objective is to accurately position and inject seeds into the soil, being able to operate with the most varied sizes and types of seeds (Figure 7.f).
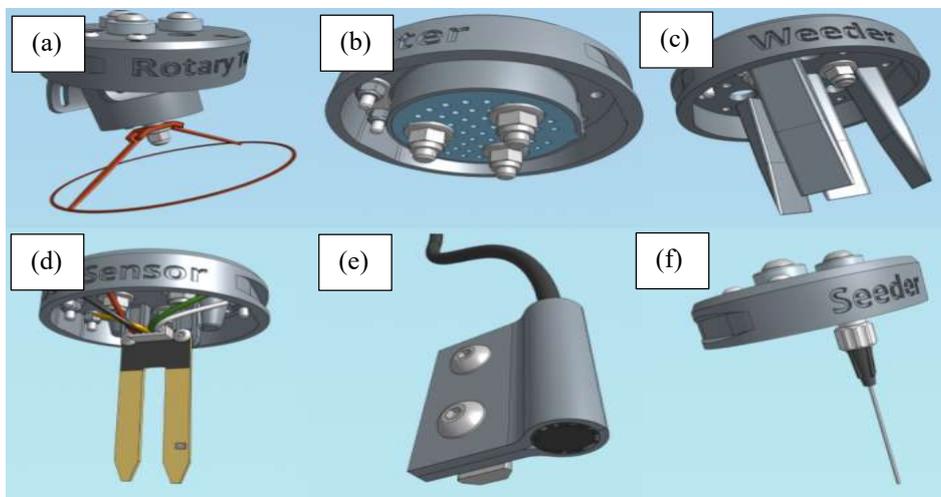

Figure 7. Auxiliary tools FARMBOT: Rotative Tool (a); Irrigation Nozzle (b); Weeding Claw (c); Soil Sensor (d); Camera (e); Injector Nozzle (f) (adapted from Farmbot, 2021).

3.4 Autonomous robots

Autonomous robots are robots that can accomplish desired goals in unstructured environments and with reduced workspace without human assistance, such as inside agricultural greenhouses. Until the present stage of the development of new technologies, the use of robotics is being mainly stimulated by the economic return generated and efficiency in the differentiated application of inputs. However, robotics aims to simultaneously increase efficiency in the management of agricultural production combined with a gradual minimization of destructive and undesirable impacts on the environment (Hackenhaar, 2015).

Fruit harvesting is the most complex in terms of economically viable automation. Such advances in the automation of industrial activities and operations have served as motivation for various agricultural tasks (Porsch et al., 2019). Fruits usually need extra care in their harvest, as they are a more fragile products than grains and other types of vegetables. Harvesting strawberries, for example, is considered an "art", as it is one of the product that can be more easily damaged, where the fruit is picked according to its size and surface shade, similar to tomatoes. An example of an autonomous robot for harvesting strawberries is the robot NORONN, created by a Japanese company (Figure 8.a), robot OCTINION (Figure 8.b, 8.c). For mini-tomato harvesting, there is the ROOT AL robot (Figure 8.d) and the ECOROBOTIX (Figure 8.e, 8.f). In summary, robotic systems are composed of a set of cameras that read the surfaces of the fruit whose end effector is a robotic claw.
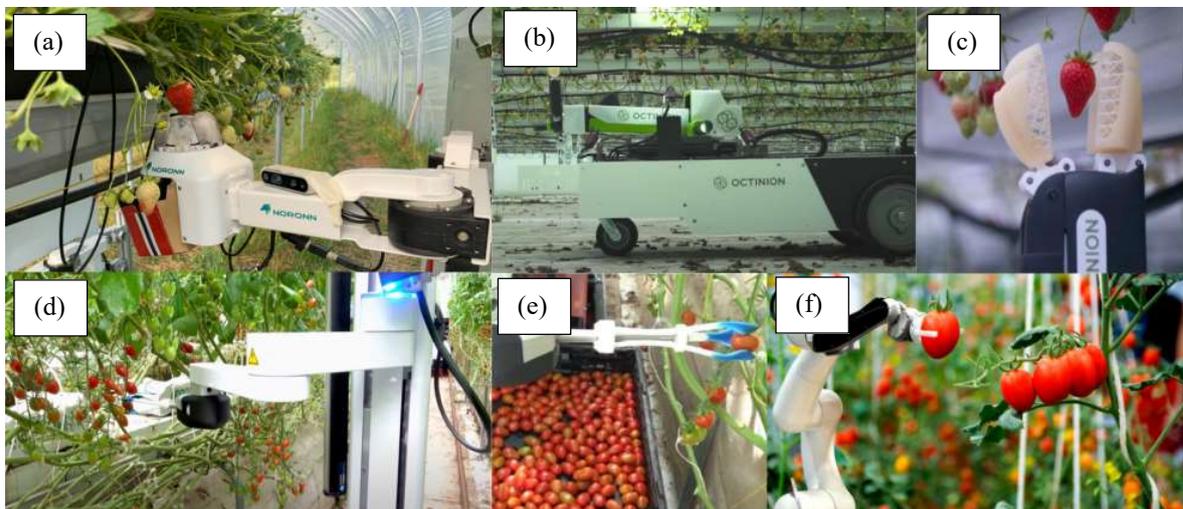

Figure 8. Robot for harvesting in greenhouses: Robot NORONN (a); Robot OCTINION (b); Robot ROOT AL (c); Robot ECOROBOTIX (d) (adapted from FreshPLaza, Farmfor, GranBio, 2019).

Another example of an autonomous robot for harvesting is the SWEEPER, developed to aid in the cultivation of peppers. However, this project faces challenges similar to low hardness fruits (sensitive fruits), and most of these robots are still only applied in greenhouses due to the greater ease of navigation between the aisles and benches and in the detection of fruits (Sweeper, 2018).

The SWEEPER robot (Figure 9) is composed of a platform that has a robotic arm and a clamp-type claw system, in addition to a set of cameras for product analysis, which moves inside the greenhouses using rails located between the planting rows in the protected crop. (Sweeper, 2018).

Figure 9. SWEEPER robot for harvesting peppers (adapted from Sweeper, 2018).

Finally, there is the autonomous robot model for the manipulation and processing of vegetables, being responsible for the transport of vessels from trajectories coded by the user. Such a robot is called the HV-100 (Figure 10) and navigates from two distance measurement systems and infrared sensors that can read a reflective reference tape. (Agtecher, 2017).

Figure 10. SHV-100 robot for handling vegetables (adapted from Greenhouse Grower, 2016).

4. CONCLUSIONS

Robotic systems have not yet been fully implemented in agriculture, due to a series of factors, such as the fragility of mechanical systems, mechanical technology with high added value, in addition to working under the limit of the capacity that the machine can offer. The discussion of new technologies and equipment in the rural robotization process is extremely incipient, as well as the analysis and discussion of the impact they may have on the rural work process. The fact that technological development has reduced the number of rural workers around the world is indisputable, given that the current technological development is more exclusive for workers. The machines changed and revolutionized the way of life of the farmer. The modern farmer has evolved a lot compared to his ancestors, but he still faces many challenges with the harmful effects of certain more intense cultivation techniques.

In this article, a survey of the state of the art on the application of robots in agriculture was performed, with a greater focus on agricultural greenhouses. It was possible to define the main constructive aspects of the greenhouses commonly used in addition to the workspace for a Gantry robot, considering that it has 3 degrees of freedom (3 translations). Additionally, it was observed the gaps to be filled about to with concerning the lack of robotization in some agricultural cultures, such as harvestingvfruits inside the greenhouses, since the existing mechanisms are intended for tomatoes and strawberries.

Thus, during the development of the article, some improvements were observed. Among these improvements, there is the fact that there are no commercially accessible models of robotic systems for small rural producers, considering that the cost of having an automated and robotized greenhouse is high. However, it is necessary to develop "low-cost" robotic mechanisms, considering that the activities conducted inside the greenhouses, such as planting and harvesting the most diverse cultures, directly affect the physical health of workers.

When it comes to Cartesian and Gantry-type robots, there is an absence of robotic systems that offer real multifunctionality, such as having in the same robot some essential functions for protected cultivation, that is, irrigation, spraying, control of weeding and harvesting coupled in the same mechanism. As for autonomous robots, the big challenge faced is precisely the control of the trajectory within the protected cultivation environment since the workspace is restricted, in addition to the high cost of obtaining a robot that performs the functions autonomously. Thus, there is a proposal for a self-aligning mechanism that allows the use of less costly and accurate guides and components, maintaining the efficiency of operation and functioning of the robotic system to be actuated (Machado et al., 2021).

Therefore, it is concluded that autonomous robots, despite their versatility of operation, use a lot of space inside the greenhouses, precisely because they move over corridors and rails, spaces that could be used with new flat benches. Thus, a Gantry structure could be used so that these robots work and are coupled to the gantry, having all their movements and degrees of freedom suspended from the benches.

As a suggestion for future work, it would be extremely important to develop a project for a robotic greenhouse for learning purposes, both in schools and universities, being possible to build a model on a reduced scale. In addition, a study involving robotization in the theme of "vertical farms" would enable new fronts of study and research.

5. ACKNOWLEDGEMENTS

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