OPTIMIZATION OF THE ROBOTIC TECHNOLOGICAL EQUIPMENT DESIGNATED FOR WORKING IN GREENHOUSES

PhD thesis – Abstract

For obtaining the scientific title of PhD with the
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1. THE IMPORTANCE AND NECESSITY OF THE THEME. OBJECTIVES AND STRUCTURE OF THE THESIS

1.1. The importance and necessity of the theme

A robot is a device that can be programmed to perform certain repetitive tasks, including handling various objects.

From the point of view of applications, 4 types of industrial robots are distinguished [22]: non-servo robots (mainly used to move and move objects), servo robots (which can perform several tasks, through integrated manipulators and effectors), programmable robots (which can store a number of commands in a database and perform various tasks multiple times), computer programmable robots (which are essentially servo robots which can be controlled remotely, through a computer).

With the introduction of robots in agriculture, agricultural productivity started to increase. Agricultural robots (agrorobots) replace the physical labor of farmers, performing slow, repetitive and often cumbersome tasks [17],[2]. Among the activities carried out with the help of agrorobots are [1]: harvesting and fruit picking, crop maintenance, autonomous mowing, pruning / grooming, sowing, planting, spraying, crop thinning / nursery, phenotyping, crop sorting and packaging, making utility platforms.

The use of robots in agriculture involves addressing some issues [7] that relate to:

- autonomous navigation (with field geometry planning, robot path planning, movement planning, satellite / GPS assisted navigation, navigation based on the position of plants or trees)
- identification of fruits, their degree of maturity and their growth environment
- interaction with fruits and their growing environment

In order to be effective, a fruit-picking robot must first correctly identify a ripe fruit, and secondly, not damage the fruit when picking it. If the identification of the ripe fruit is mainly done using optical systems ([4], [7], [21]), the interaction of the robot with the fruits requires the constructive optimization of the prehension elements ([18], [12], [24]).

1.2 Objectives of the thesis

The main objective of the thesis is the constructive and functional optimization of the component elements of the robotic systems used in greenhouses, in order to increase the qualitative and quantitative performance of the vegetable (tomato) harvesting process,

and the integration of these elements in a prototype of a robotic system to assist the process harvesting in greenhouses.

In order to achieve this objective, it was considered necessary to fulfill the following subsumed secondary objectives:

OS1: Analysis of market requirements regarding the possibilities of using robotic systems in greenhouses in the Western area of Romania (Timiș and Arad counties)

OS2: Analysis of market requirements regarding the particularities of the structural and functional elements of the prehension systems used in greenhouses

OS3: Critical analysis of the main prehension systems used in agriculture

OS4: Determination of optimal solutions regarding ripe fruit identification systems

OS5: Determination of optimal solutions regarding the interaction between the prehension system and ripe fruit

OS6: Integration and optimization of prehension and optical components in a robotic structure for greenhouse work

1.3 Structure of the thesis

The work is structured on 7 chapters, conclusions and appendices.

The first chapter presents the importance and necessity of the chosen theme and Romania's position in relation to the situation of the areas cultivated in greenhouses and the number of agricultural holdings of the greenhouse type at the level of the European Union. Also, the main objective of the thesis and the secondary subsumed objectives, as well as the structure of the thesis, are presented. **In the second chapter**, an analysis of the possibilities of using robotic systems in greenhouses is presented. **Chapter 3** presents a critical analysis of the current state of the main prehension systems used in agriculture. **Chapter 4** contains theoretical and experimental research on the particularities of the structural and functional elements of the prehension systems used in greenhouse works. **Chapter 5** includes experimental research on the optimization of ripe fruit identification systems. **The sixth chapter** presents experimental research on the interaction between the prehension system and ripe tomatoes. **Chapter 7** contains research on the integration and optimization of components in a robotic structure intended for work in greenhouses and solariums. The conditions imposed by the terrain, a schematic diagram of a robotic technological equipment (RTE) for picking tomatoes and the specific mobility system in greenhouses are presented. Finally, **the conclusions**, personal contributions and the attached materials used to carry out this research are presented.

2. ANALYSIS OF THE POSSIBILITIES OF USING ROBOT SYSTEMS IN GREENHOUSES

2.1 Preliminary conditions

Although in the Western region of Romania the area cultivated with vegetables in solariums and greenhouses exceeded 110 ha (the minimum value was 116 ha in 2010), in Timiș County this area did not exceed 35 ha (the maximum value was 31 ha in 2011) [1]. According to [1], the share, at the national level, of individual agricultural holdings is increasingly higher in terms of growing vegetables in solariums and greenhouses, including in the West region (from 76.72% in 2010 to 98.76% in 2020). At the level of Timiș county, vegetables were grown in solariums and greenhouses exclusively within individual farms.

Starting from these assertions, in the framework of the doctoral research, in the first part, the analysis of the opinion of the owners of greenhouses in the Western area of Romania was pursued.

2.2. Description of the research methodology

The analysis is based on a questionnaire that was distributed to 30 people, horticultural producers in the Western area of Romania.

The questionnaire includes 16 questions. The target audience was 30 people, producers and owners of greenhouses and solariums. The distribution of the questionnaire took place in the rural area of Timiș and Arad counties, in 2016.

Of the 16 questions, 3 analyze *the relationship between cultivated plant – agrotechnics – cultivation conditions*, 5 analyze *the management and marketing of the holding*, 4 analyze *the possibility / appetite / interest of producers for the introduction of robotization* and 4 analyze *the level of qualification and other individual and social environment characteristics*.

2.3. Results and discussions

In the following, the main results obtained following the application of the questionnaire are presented.

Thus, the majority of respondents (73%, 22 out of 30) use soil cultivation methods, directly on one level, 27% use overlapping soil cultivation methods (27%, 8 out of 30), while in 2016 in the rural area of Timiș county, none of the respondents used aquaponic culture methods.

From the responses received, it appeared that all producers using a sandy soil (21 out of 30) or silty soil (2 out of 30) maintain it at the optimal nutrient conditions necessary for production, and all producers using a loamy soil (5 out of 30) or clay (2 out of 30) does not consider it maintained to provide optimal nutrient conditions.

Regarding the type of crop (question 5), all the surveyed producers have crops of tomatoes, peppers, cucumbers, eggplants, lettuce, green onions. Half of them also produce other vegetables – in this case green beans and peas.

None of the producers who responded to the questionnaire use robots at work (question 3). However, the level of knowledge of producers regarding the use of robots in greenhouses varies: 13.33% of respondents do not know the field at all, 46.67% have little knowledge in the field, 33.33% know somewhat more in the field and only 6.67% of respondents know the field and have also seen applications. No respondent is an expert in the field of using robots in greenhouses.

From the analysis of the answers provided, it is evident that the majority of respondents (40%) prefer to use robotic means for harvesting, followed by crop maintenance and product sorting and packaging in order of preference. The last options in order of respondents' preferences is to use robots for crop monitoring and sowing.

Regarding harvesting, most respondents expressed their preference for the use of robotic means. Regarding crop monitoring, the majority of respondents believe that it does not matter if they use robotic means or not. Regarding crop maintenance, most respondents consider it not important to use robotic means. Most of the respondents say that they are not interested in using robotic means for sowing. Product sorting and packaging is an area where most respondents feel it is irrelevant whether or not they use robotic means.

When it comes to the decision criteria for using robotic solutions in greenhouses, the majority of respondents (30%) consider the high reliability of the solution (i.e. the operational safety of the device, its ability to function without failures) to be very important. In descending order of importance, respondents consider ease of handling, flexibility and the fact that the solution represents a small investment to be very important. At the opposite pole, 40% of respondents consider that the flexibility of a technical solution for greenhouses is not important at all, but neither the low investment value nor the possibility of easy handling are important.

Regarding the possibility of association to use a robotic solution in greenhouses, the majority of respondents (44%, 13 out of 30) consider it unlikely, 23% consider it likely, 23% consider it possible, and 10% believe that it is impossible for producers to be able to associate in order to use robotic means in greenhouses. This answer reflects the state of affairs highlighted in the INSSE statistics [1].

2.4. Partial conclusions

From the previous analysis, it emerges the maximum importance of the research aimed at identifying application solutions suitable for the specific national conditions for the robotization of works in greenhouses.

At the same time, the most important aspects related to the use of robots in agriculture can be grouped into 4 large categories [8]:

1. **Performing appropriate agricultural functions** (main utility functions), in descending order of their importance: harvesting and packaging, plant protection and weed control, transplanting and sowing, environmental monitoring and management, watering and fertilizing, the possibility of achieving a wide variety of tasks, handling various tools
2. **Performing support tasks** (functions or auxiliary utility functions) – which are, in descending order of their importance: guidance and navigation, selecting and grabbing fruit, mapping and locating, avoiding obstacles, dispatching vehicles for transport
3. **The minimum cost of equipment** – consists of the following groups, in descending order of their importance: maintenance costs, total investment costs, availability, flexibility, reconfigurability, knowledge transfer).
4. **Technical and structural features required**, which must result from the structure of the robot and which are, in descending order of their importance: 4-wheel steering system, ultrasonic sensors, 2 controllers (Arduino and/or Raspberry Pi), stereo vision binocular, power supply system, harvesting system - gripper with 5 degrees of freedom, laser systems for linear scanning, 2/4 motors, drivers, industrial / on-board computer, camera, GNSS receiver, end effector

Other aspects to consider when designing a robotic greenhouse "helper" include the shape of the gripper, optimized software algorithms, the use of specific artificial intelligence tools for real-time optimized crop classification.

All these needs can be addressed using automated solutions in greenhouses such as harvesting robots. In the following, we will present a functional greenhouse harvesting robot concept used for harvesting ripe tomatoes.

3. CRITICAL ANALYSIS OF THE CURRENT STATUS OF THE MAIN GRIP SYSTEMS USED IN AGRICULTURE

3.1. The current state of knowledge in the field of prehension solutions applicable to vegetable harvesting systems

1. From the point of view of **origin**, two types of prehension systems are distinguished: natural prehension systems (of which the most evolved is the human hand) and artificial prehension systems (prehensors) [19]

2. From the point of view of **specific applications**, the prehension systems are classified in [20]:

2a) Industrial prehension systems

2b) Prehension systems for medical applications

2c) Micro and nano prehension systems

2d) Prehension systems for light materials

2e) Prehension systems for fragile objects, etc.

3. According to the **principle of operation**, grippers can be classified into: mechanical, ingressive, electromagnetic, electrostatic, suction type, air jet or cryogenic [5].

4. According to the **size order** of the manipulated objects, the grippers can act on a macro (above 100 μm), micro (from 100 μm to 100 nm) or nano (below 100 nm) scale.

3.2. Possibilities for the integration of prehension solutions in robotic harvesting systems

In the agricultural field, prehension systems are used especially for harvesting fruits and vegetables. The need not to damage the harvested products and the variability of their sizes generally require that the grippers used for harvesting be mechanical and able to act at a macroscopic level. So, according to the classification made in [5], the grippers that could be used in agriculture are: friction grippers, claw grippers, suction grippers.

The agricultural environment is a partially unknown environment. Even if the exact position of a plant (stem) on which the fruits are to be picked is known, the exact position of a ripe fruit on the plant is not known.

Therefore, even though the mobility system of a harvesting robot can be designed and programmed relatively easily, the system for detecting and picking ripe fruits without damaging them is more difficult to design and program.

In 2015, Feng et al. [6] proposed a robotic system for harvesting tomatoes from greenhouses. One such robotic system consists of a platform that moves on a rail system in a greenhouse. A combination of a camera and a laser system is used to detect ripe fruit. The control structure of such a robot takes up space, and in addition, a greenhouse where this device could be used must be equipped with rails for the robot to travel on.

In 2016, Biquing et al.[2] they realized the concept of a robot to pick cherry tomatoes, which they tested on an experimental stand. The testing involved 3 stages: 1 – testing the tomato identification mode, 2 – testing the automated response, 3 – testing the efficiency of the parallel control system. The performance of the system was measured by the failure rate (percentage of damaged tomatoes at picking). For the proposed system, the failure rate is between 1.21% and 1.35%, significantly improved over the failure rate in the classical case (which is over 7%).

In 2017, Lili et al. [13] presented the concept of an autonomous robotic system for picking tomatoes. It consisted of an independently movable 4-wheeled platform that supported a 5-degree-of-freedom robotic arm, a greenhouse navigation system, and a stereo video system for ripe fruit detection. The navigation system correctly identified the road in the greenhouse with an error of 80 mm. The robotic arm could lift up to 1.5 kg. The success rate of the video system for recognizing ripe tomatoes was 93%. At distances less than 600 mm, the positioning error was less than 10 mm, and the red recognition time was about 15 s / tomato, with a success rate of about 86%.

The idea of calculating real distances based on pixel distances in an image has also been described in [11]. This paper describes how, using two cameras, the coordinates of the fruit to be picked can be determined and the movement of the robotic arm to the fruit can be calculated.

3.3. Realization of a robotic technological equipment of our own design for picking tomatoes in greenhouses

Considering the results presented in [6], [2] or [13], the current work aimed to design and test a robotic technological equipment that would move in a greenhouse and pick tomatoes. The system will consist of a self-propelled 4-wheeled platform that will support the central control unit, robotic arm and fruit detection system.

Unlike previous research, the navigation system does not assume the existence of rails in the greenhouse (as in [2]). The proposed navigation system assumes the existence of rows of tomatoes, and the robot moves in a straight line until it reaches the end of a row. In this way, the navigation system will be oriented to detect a new plant in a row rather than to detect the path in the greenhouse.

The ripe fruit detection system proposed in this work does not use two cameras (like the systems proposed by [13] or [11]) to detect a ripe fruit and the distance to it, but uses only one camera, but which is provided with additional lighting conditions, to make images as close to reality as possible. Instead of two cameras taking two images simultaneously, the proposed solution uses a single camera placed on the gripper, which, in order to determine the relative position of the tomato to the gripper, collects two images at a known distance in space.

4. THEORETICAL AND EXPERIMENTAL RESEARCH ON THE PARTICULARITIES OF THE STRUCTURAL AND FUNCTIONAL ELEMENTS OF THE GRIPPING SYSTEMS USED FOR WORK IN GREENHOUSES

4.1. Objectives of the research

- Analysis of the work process of a gripper
- Conception of a gripper used in robotic systems in greenhouses
- Functional integration and optimization of the proposed gripper

4.2. Description of the research methodology

The research was carried out according to a methodology whose operational scheme is presented in Figure 1.

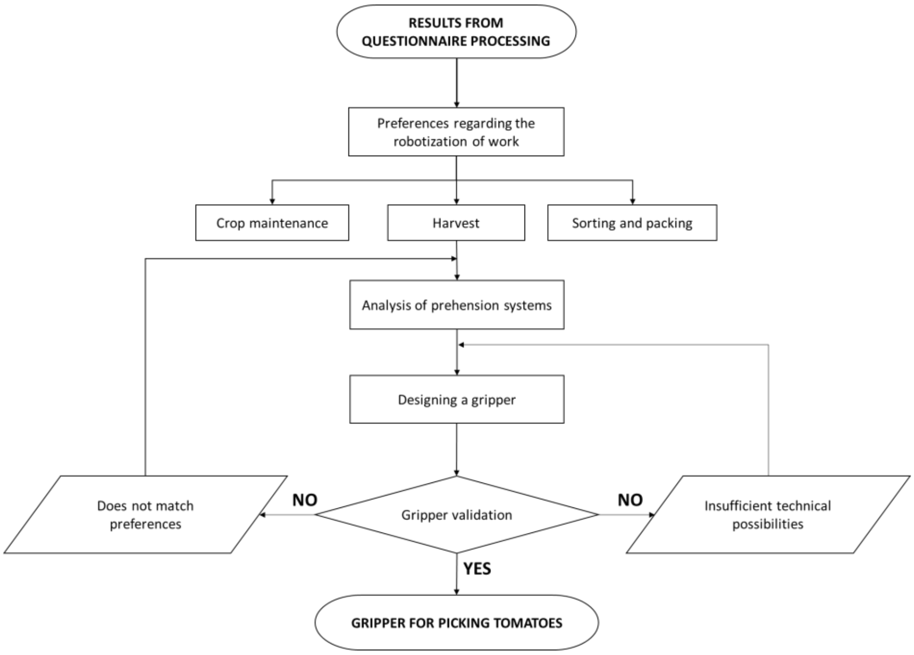

Figure 1. Methodology of research - scheme

4.3. Investigating the working process of a gripper

In 2014, Bolboe, Starețu and Alexandru [3] made an anthropomorphic gripper with two fingers, inspired by the human hand. The experimental stand consists of 5 subsystems: actuator / motor, motion transmission system, sensor system, command and control system, gripper itself.

The clamped object centers itself, depending on the applied force, and the gripping process continues until both sensors register a maximum allowed value.

4.4. Design, integration and functional optimization of a gripper used in robotic systems in greenhouses

A tomato picking robot, hereinafter referred to as RADAR 00 (Robot Automat De Adunat Roșii – Automatic Tomato Picking Robot, experimental model level), consists of the following components: I – mobile platform, II – control unit and power system, III – appropriate robotic arm.

The design of the gripper involved:

- Identification of a suitable mechanical system in commercial condition for harvesting tomatoes
- Adaptation of the identified system to the conditions required by tomato harvesting in greenhouses

The prehension system consists of the MG995 servo motor actuated by commands received from the Arduino board and the actual prehensioner, which, in a greenhouse, can be a two-arm (finger) system.

Similar to those described in [5], the prehension system for ripe tomatoes must achieve the following:

- Identifying a ripe tomato on the plant
- Bringing the gripper closer to the ripe tomato
- Making contact and catching the tomato without damaging it
- Detaching the tomato from the plant
- Moving the detached tomato to a collecting container
- The release of the tomato

4.5. Partial conclusions

Starting from the identified needs of the producers in the area, the most frequent option was identified in their preferences for the use of a possible robotic system to assist the processes in the greenhouses. This option is to use robots for harvesting.

Harvesting requires the existence of a robotic arm equipped with a gripper, and the percentage of fruits/vegetables picked without being damaged depends on the particularities of the gripper and how it acts.

Considering the specificity of the harvest that is analyzed in the present research (picking ripe tomatoes in greenhouses), we opted for the use of a two-finger gripper, mounted on a robotic arm operated by 5 servomotors and moved between the rows of tomatoes in a greenhouse with using a mobile platform.

In the following, essential elements of the proposed robotic system will be described:

the process of identifying ripe fruits, the calibration of the gripper to pick tomatoes without damaging them, and the integration of these subassemblies on an autonomous system that moves in the greenhouse.

5. RESEARCH ON THE OPTIMIZATION OF RIPE FRUIT IDENTIFICATION SYSTEMS

5.1. Objectives of the research

- Identification of ripe fruit characteristics for the San Marzano variety
- Writing an algorithm for the color recognition of a ripe fruit
- Writing an algorithm for the recognition of the outline of a fruit
- Optimizing the proposed algorithms and testing them under real conditions
- Proposing constructive solutions to optimize the ripe fruit identification system

5.2. Materials and methods used to optimize ripe fruit identification systems

The testing of ripe fruit identification algorithms was done using tomatoes of the San Marzano variety, grown in our own greenhouse, in Lugoj, whose GPS coordinates, according to Google Maps, are 45.686333; 21.908737 (latitude 45°41'10"N, longitude 21°54'31"E).

For this research, the maturity stages of tomatoes were used according to the classification in [23], which, from left to right, include: raw green, ripe green, breaking, turning, beginning to ripen (pink), almost ripe (light red), ripe (red). Tomatoes are usually harvested when they start to ripen.

Collecting a digital image is done with a photo sensor (camera). In the creation of the robot, a camera module with a wide angle of view, the possibility of adjustable focus, adapted for Raspberry Pi was used.

In the lighting conditions provided by RADAR 00 - the robotic structure proposed in this research (2 side lamps), the settings for the camera module must also take into account the heating time of the sensor and the correction of a possible rotation of the camera due to the way of construction.

The detection of a fruit, followed by the analysis of its vegetation stage, is done through a working algorithm assisted by a practical controller, realized in our own design by using a Raspberry Pi type microcontroller board.

The image processing program for ripe fruit detection was made using the Python programming language, a general-purpose high-level programming language. This language builds and object-oriented approach to help programmers write clear logical code for small and large-scale projects. The program designed for the detection of ripe fruit works both integrated into the RADAR 00 system and independently, on any system on which it is installed, allowing, like the program developed in [10], its easy use and independent of the operating system chosen.

The image processing routine involves gathering an image, then processing its attributes to extract information. The image collection is done with the help of a stand-alone function, which we specially designed. This function will be used several times during the program to detect the position of a fruit. Image processing, with a self-designed red filter, is programmed with another special function.

5.3. Results and discussion on the ripe fruit identification system

In a first phase, the color detection program was tested on the color spectrum as it appears in Microsoft Windows applications (Figure 2 and Figure 3).

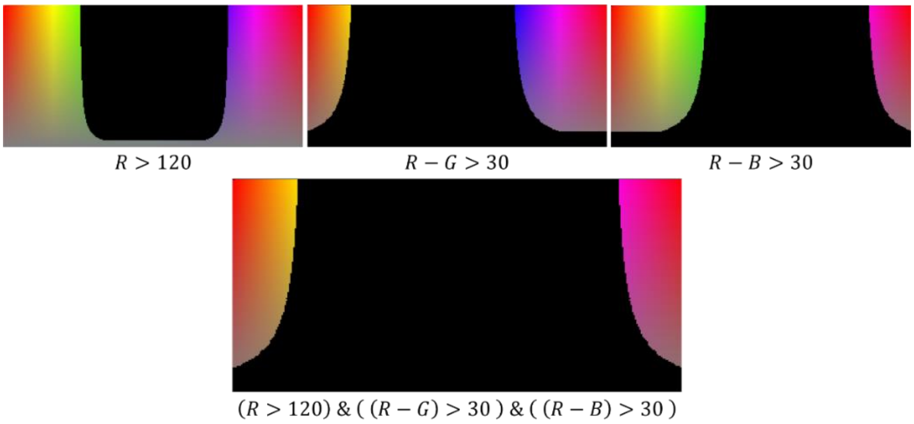

Figure 2. Permissible colors for a ripe tomato, based on the color spectrum and the 3 components of the red color filter

Figura 3. The amount of red related to each stage of tomato ripening

5.4. Partial conclusions

In this chapter, the main technological characteristics for tomatoes of the San Marzano variety have been identified. These influenced the architecture of the concept of robotic technological equipment for harvesting tomatoes: a gripper with dimensions compatible with the dimensions of the tomato was used, motors of sufficient power were used to pick the tomato, the algorithms for recognizing the ripe fruit were calibrated according to the standard dimensions of a ripe tomato.

Also in this chapter, algorithms were built to detect the color red, respectively the position of a red tomato. The optimization of the ripe fruit identification process involves both the optimization of the recognition algorithms and the constructive optimization of the robotic system.

The optimized concept of the robotic system and the algorithms for detecting ripe tomatoes and their position in relation to the gripper were tested in real conditions, in our own greenhouse at Lugoj.

In the following chapters, the prehension system of ripe fruits will be studied and, finally, the concept of robotic technological equipment for harvesting tomatoes in the greenhouse will be presented as a whole.

6. EXPERIMENTAL RESEARCH ON THE INTERACTION BETWEEN THE GRIPPING SYSTEM AND RIPE TOMATOES

6.1. Objectives of the research

- Testing the prehension system of the proposed robotic system for harvesting tomatoes from greenhouses
- Establishing the optimal structure and technical-functional parameters of the robotic system for harvesting tomatoes from greenhouses
- Functional optimization of a gripper dedicated to picking tomatoes

6.2. Materials and methods used to study the interaction between the prehension system and ripe tomatoes

In order to achieve the previously stated objectives, an experimental stand was created, on our own design and execution, in order to analyze the data obtained from the interaction of the gripper with 10 samples of tomatoes.

The experimental stand integrates the own designed prototype of RTE (RADAR 00) for picking tomatoes with a support with a base made of an elastic material (flexible surface) on which the tomato is placed and two comparators that measure the deformation of the tomato. Force sensors were fitted to the RADAR 00 gripper, lights being also used in this case. Details are shown in Figure 4 and Figure 5.

In Figure 4 and Figure 5, the following notations were used for details: 1 – the tomato support; 2 – tomato (sample); 3 – mechanical comparator; 4 - electronic comparator; 5 – camera module; 6 – light sources; 7 – robotic arm; 8 – mobile platform; 9 – the communication system with the robot; 10 – detail of the experimental stand, shown from another angle in Figure 5; 11 – gripper finger; 12 – gripper finger; 13 – servo motor MG995; 14 – force sensor; 15 – force sensor.

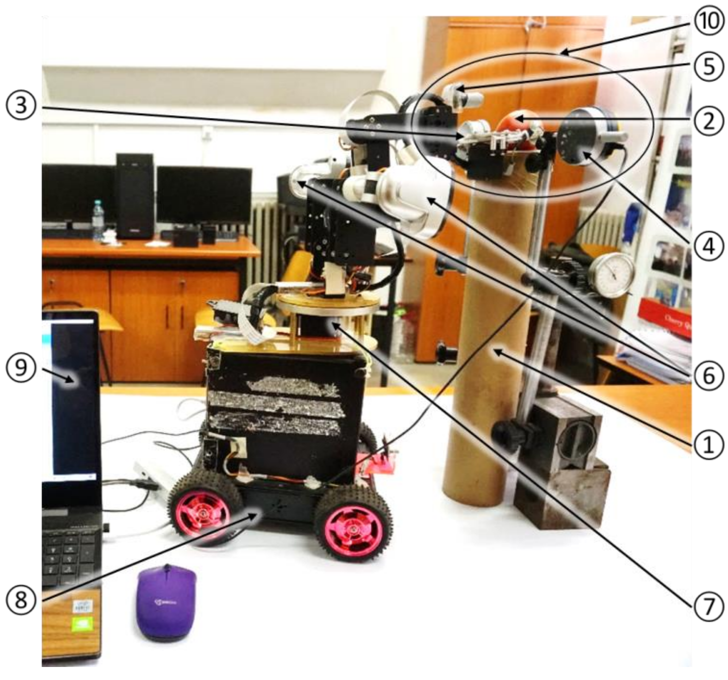

Figure 4. Experimental stand in the laboratory for the research of the interaction between the gripper and the tomato in the main view (personal archive)

Figura 5. Experimental stand (upper view)

The tomatoes for which the experiments were carried out are classic round tomatoes that come from the SupeR Greenhouses in Biled [16] and have a diameter of 50 mm. The 10 samples of tomatoes were randomly selected from a sample of 100 pieces.

After sampling, each tomato was permanently marked with a number from 1 to 10 (the sample code), then its dimensions and mass were measured.

For each tomato, two longitudinal diameters were measured along directions perpendicular to the axis of the tomato and two transverse diameters along directions perpendicular to the planes determined by the axis of the tomato and the longitudinal diameters. The longitudinal diameter of the tomato is the arithmetic mean of the measured longitudinal diameters, and the height of the tomato is the arithmetic mean of the measured transverse diameters.

The mass of each tomato was determined in grams using an OHAUS Discovery analytical balance with an accuracy of 10^{-5} grams.

In order to carry out the experiment, the following data were recorded:

- Mass m_i of each of the 10 analyzed tomatoes ($i = \overline{1,10}$)
- Mean transverse diameter $D_{med,i}$ for each of the 10 analyzed tomatoes ($i = \overline{1,10}$)
- Height $H_{med,i}$ of each of the 10 tomatoes analyzed ($i = \overline{1,10}$)
- Angle U corresponding to the servo arm
- Deformation ΔD_m read by mechanical comparator
- Deformation ΔD_e read by the electronic comparator
- The value of the specific force read on the right force sensor, $F_{spec,1}$, corresponding to each angle U and each tomato i ($i = \overline{1,10}$)
- The value of the specific force read on the left force sensor, $F_{spec,2}$, corresponding to each angle U and each tomato i ($i = \overline{1,10}$)

From the point of view of the approach and use in the real process, the data collected are divided into:

- controllable data (related to sensor records)
- partially controllable data (related to the interaction between the prehension system and the tomato)

- uncontrollable data (related to the tomato and which cannot be precisely measured until after the tomato has been picked)

The data obtained experimentally were analyzed from the point of view of the relative deformation, the angle made by the arm of the servomotor with its axis and the force applied to the tomatoes, resulting in the following analyses:

- The variation of the relative deformation, ΔD_{rel} on the angle of the servomotor, U

$$\Delta D_{rel} = f(U) \quad (1)$$

- The variation of the average specific force, F_{spec}, on the angle of the actuator, U

$$F_{spec} = f(U) \quad (2)$$

- The variation of the relative deformation, ΔD_{rel}, on the average specific force, F_{spec}

$$\Delta D_{rel} = f\left(F_{spec,i}\right) \quad (3)$$

6.3. Results and discussions

For the 407 complete data sets considered, a correlation analysis was performed, after which the average deformation, the variation of the specific force and the angle of the actuator were chosen for study.

The equation which describes best the dependence between the relative deformation of tomatoes, ΔD_{rel} and the angle of the actuator, U, is a multiplicative one, for which the correlation coefficient is 0,9995, and the determination coefficient is 99,89% (hence the model explains 99,89% of the variability in ΔD_{rel}):

$$\Delta D_{rel} = e^{0,787229 \cdot \ln U} = U^{0,787229} \quad (4)$$

The mean square error for this model is 0.0598143 and the standard error of the estimate is 0.11428 at the 95% confidence level.

In the case of the dependence of the specific force on the angle of the actuator, the data are best explained by a multiplicative model, for which the correlation coefficient is 0.9998 and the coefficient of determination is 99.96%. The equation that describes this model is:

$$F = e^{1,50249 \cdot \ln U} = U^{1,50249} \quad (5)$$

The mean square error for this model is 0.110589 and the standard error of the estimate is 0.136569 at the 95% confidence level.

The regression equation that best describes the dependence between relative deformation and specific force is

$$\Delta D_{rel} = \left(0,2024 \cdot \sqrt{F}\right)^2 = 0,04096 \cdot F \quad (6)$$

With a correlation coefficient between variables of 1, this equation explains 99.99% of the variation in ΔD_{rel} as a function of F. The mean squared error for this model is 0.0366949 and the standard error of the estimate is 0.0447245, at a 95% confidence level.

6.4. Feasibility analysis of the obtained solutions for transposition to other tomato varieties

Analyzing the data set collected during the experiment, we obtained a first relationship between these variables:

$$F = 4,2272 \cdot m + 0,0158618 \cdot U + \\ + 24,3837 \cdot 100 \cdot \Delta D_{rel} - 10,826 \cdot H_{med} + 5,52186 \cdot D_{med} \quad (7)$$

The equation explains 99.9942% of the variability in the average applied force, F. Eliminating the variable U, which is not significant at the 95% confidence level, yields the following model for the average force:

$$F = 4{,}23208 \cdot m + 24{,}4192 \cdot 100 \cdot \Delta D_{rel} - 10{,}8636 \cdot H_{med} + 5{,}55715 \cdot D_{med} \quad (8)$$

This equation also explains 99.9942% of the variability in the specific force, F, but in this case the P values associated with each input variable are zero. Consequently, the model does not need to be simplified.

This equation can be used to calculate the average specific force of the gripper if it is desired to pick a tomato for which the mass, average height, average diameter are known, for a maximum relative deformation established initially.

In practice, if the average diameter and average height of a mature tomato of a particular variety can be assumed to be known, the mass of the tomatoes cannot be effectively determined before they are picked. In conclusion, a more realistic equation for determining the average downforce should not take into account the mass of the tomato.

Such an equation, which would determine the average gripping force of the tomato according to known, a priori measurable data, is:

$$F = 24{,}1464 \cdot 100 \cdot \Delta D_{rel} - 8{,}77955 \cdot H_{med} + 8{,}9836 \cdot D_{med} \quad (9)$$

This equation explains 99.9844% of the variability in F, and the P values associated with each factor in the equation are zero—thus all factors are significant at the 95% confidence level.

We applied the formula for the average gripping force to 15 varieties and hybrids of tomatoes produced at SCDL Buzău between 1957 and 2015, for which the average height and average diameter of the fruits are known.

In the case of tomatoes of the San Marzano variety, whose characteristics were presented in detail in Chapter 5, subchapter 5.1 ($H_{med} = 90\ mm,\ D_{med} = 40\ mm$), the application of formula (9) leads to the following conclusions:

- A maximum pressure force of 950 U.M. (the limit imposed for pressure sensor readings under laboratory conditions) corresponds to a relative deformation for tomatoes of 0.57%.
- Under field conditions, the maximum value for the downforce value of 700 U.M. was used, which, substituted into equation (9), shows that the maximum deformation that a San Marzano tomato can undergo when picked using the proposed robotic system is of 0.47%.

6.5. Partial conclusions

A logical step in the validation of an RTE used for harvesting involves testing the prehension system and establishing its optimal technical-functional parameters when harvesting ripe fruits.

The system was tested in laboratory conditions and dependence relationships were identified between the angle of the servo motor, U, the variation of the specific force on the tomatoes, F and their relative deformation, ΔD_{rel}.

The dependences $\Delta D_{rel} = f(U)$ and $F = f(U)$ use the servo angle as an independent variable, but are highly dependent on the tomato dimensions, dimensions which, within certain limits, are specific to the tomato variety picked. A more realistically formulated dependence is $\Delta D_{rel} = f(F)$, which can be applied in any circumstance, for any tomato of a given variety.

Based on the experimental data, formulas were determined for the relative deformation ΔD_{rel} as a function of the specific pressing force F, the mean diameter of the tomato D_{med} and the average height of the tomato H_{med}. These formulas allow the establishment of upper limits for the specific pressing force recorded by the sensors so that the relative deformation of the tomato does not exceed a certain value.

Also based on these formulas, the upper limit imposed for the value read by the force sensor when the RTE was used in real conditions in the greenhouse was also validated.

In the following, the routine for identifying ripe fruit and picking the fruit without damaging it will be integrated into a prototype RTE for picking tomatoes in a greenhouse.

7. RESEARCH ON THE DESIGN, INTEGRATION AND OPTIMIZATION OF COMPONENTS IN A ROBOTIC TECHNOLOGICAL EQUIPMENT FOR GREENHOUSE AND SOLAR WORKS

7.1. Objectives of the research

- Creating a prototype of robotic technological equipment (RTE) for tomato picking
- Integrating the identification elements of ripe fruits and the process of picking a tomato without damaging it in the created RTE
- Implementation of a mobility system specific to greenhouse conditions
- Optimizing the trajectory during harvesting
- Testing the system for actual tomato picking

7.2. Field-imposed conditions

Field experiments were carried out in our own greenhouse, located in Lugoj.

San Marzano tomatoes were grown in this greenhouse, in 4 rows of 15 plants each. The distance between plants was 35 cm, and the distance between rows was 60 cm.

7.3. Schematic diagram of an RTE for tomato harvesting

RADAR 00 was designed as a structure consisting of a robotic arm mounted on a 4-wheeled platform with independent traction, which realize autonomous movement through the greenhouse, between rows of tomatoes. Upon detecting a plant, the autonomous platform stops and searches for ripe tomatoes using image processing algorithms. When a ripe tomato is identified, another algorithm calculates the target's coordinates with respect to the grip and plans the robotic arm's movement until the ripe tomato is gripped and detached from the plant.

Thus, on a platform P equipped with 4 motors (MP1, MP2, MP3, MP4) a robotic arm is mounted consisting of: base B, segments S1, S2, S3 and gripper (claw) C. The joints of the system consist of the following motors:

- MB1, which connects the base of the robotic arm to the platform and performs rotation in the horizontal plane
- MB2 and MB3, which connect segments S1 and S2 and perform vertical rotation. The two motors are connected in parallel to increase the torque.
- MB4, which connects segments S2 and S3 and performs a rotation in the vertical plane.
- MB5, which connects the segment S3 to the gripper C and which performs a rotational movement in a plane perpendicular to the axis of the segment S3.
- MC, which actuates the gripper and which performs a rotation in the plane of the two fingers of the gripper C.

On the same conceptual basis, the functional block diagram of the robotic system is presented. The control system uses an Arduino board that communicates with a Raspberry Pi microcomputer. Input data is read by the following types of sensors:

- Lateral proximity sensor, whose readings are used by the Arduino board and which allows the detection of a plant
- Front proximity sensor, whose readings are used by the Arduino board and which allows the detection of a fruit

- Pressure sensor, whose readings are used by the Arduino board and which allows applying a force to pick the fruit
- The camera, whose readings are used by the Raspberry Pi microcomputer and which allows the detection of a ripe fruit

The RADAR 00 system contains:

7.3.1. Mobile platform – a metal robotic chassis, containing:

A. 4 motors to allow free movement in the greenhouse
B. motor control development board
C. 4 wheels
D. ultrasonic sensors to allow identification of plants in the greenhouse

7.3.2. Control unit and power system, containing:

A. Arduino Mega to control chassis motors
B. Raspberry Pi 3 for sensor data processing and image analysis
C. 12 V 5 Ah battery to power the motors that drive the wheels of the mobile platform
D. External battery to power Raspberry and Arduino
E. Voltage regulation mode to protect the components from potential overvoltages
F. Start / reset button

7.3.3. Robotic arm, containing:

A. Robotic arm with 5 degrees of freedom
B. 5 servomotors, to set the various segments of the robotic arm in motion
C. Gripper
D. Camera mode to collect images from the greenhouse
E. Pressure sensor to provide data on the prehension process
F. Auxiliary lamps to ensure optimal lighting conditions

7.4. Specific mobility system in greenhouses

The motion algorithm of the RADAR 00 robot can be described as a sequence of procedural steps that include the following successive independent functional requirements:

- Find a plant
- Find a ripe tomato on the plant
- Grab the tomato
- Twist the tomato to detach it from the plant
- Place the tomato in an adjacent basket
- Go back to the plant and start over
- If no more ripe tomatoes are found, find the next plant in turn and start a new cycle

7.5. Calculation of the optimization of the trajectory during harvesting

In order to command the movement of the robotic arm during harvesting, a program is written in Python and running on Raspberry Pi.

In order to determine the movement of the robotic arm, two images need to be processed. The first image is taken, processed and adjusted, then the robot moves a distance δ (in our case, $\delta = 0.05\ m$), the second image is taken which is processed and adjusted. Based on these calculations, the distance to the tomato is determined, i.e. the spatial coordinates (x,y,z) to which the gripper must reach. The gripper movement coordinates are also transmitted.

7.6. Actual tomato picking

For the actual picking of the tomato, it is necessary to convert the distances computed with the tomato identification program into angles by which the motors move. This is done using a own-designed algorithm (Figure 6).

Figura 6. Process of picking the tomato

7.7. Partial conclusions

The elements for identifying ripe fruits and the process of picking them without damaging them have been integrated into a specialized RTE for picking tomatoes under greenhouse conditions.

In the present chapter, the components used to create such an RTE and the justification of their choice from a functional point of view were presented.

In addition, the mobility system specific to the conditions in the greenhouse, the routine to optimize the distance to the harvest and the effective picking of tomatoes in the greenhouse were presented. For all of this we presented algorithms and code elements, made in our own design, to integrate all these aspects in the RADAR 00 prototype.

Being a prototype, the functions considered important to harvest tomatoes were developed: identifying the fruit, computing the distance to the ripe fruit and grabbing the fruit without damaging it.

The RTE works in a greenhouse, where the geometric layout of the plants is known (number of rows, number of plants in a row, approximate distance between rows and between plants) and it is also assumed that in its movement the RTE does not encounter obstacles (such as stones, boulders or pits). Because of this, it is sufficient to ensure that the distance between the chassis and the ground is 13 mm.

In this variant, the RTE picks the tomato and transports it to a container (basket). The use of more powerful engines for the platform is being considered, such that it would make possible to tow a basket in which to store the harvested fruit.

An improved version of the proposed prototype will also take into account the possibility of obstacles in the greenhouse, by increasing the distance between the chassis and the ground.

A variant in which the RTE can pick fruit at a greater distance will also be considered - by extending the segments of the robotic arm and adapting the servomotors accordingly.

8. CONCLUSIONS AND PERSONAL CONTRIBUTIONS. FUTURE PERSPECTIVES

8.1. General conclusions

The local food needs of the population are closely related to the dynamics of the agricultural labor market. The need for workers to perform activities in the agricultural field can be solved by using RTE to perform part of these agricultural jobs.

Starting from this need, the objective of the current research was to optimize, from a constructive and functional point of view, a RTE to harvest tomatoes in greenhouses.

The research focused on identifying the needs of producers and on optimizing a RTE used for harvesting from the point of view of identifying ripe fruits and picking them.

During the research, we discovered that greenhouse owners do not know the advantages of the association and use of agricultural robots, even if the application of these technologies is timely. This suggested the idea of creating showrooms where these equipments could be presented.

Also, the preferences of producers regarding the use of robots in agricultural work were identified - which substantiated the present research, to realize a RTE for picking ripe fruits.

An important aspect is the correct identification of fruits – which has been studied and for which original solutions have been proposed. It is also important to pick the fruit without damaging it. The gripper-fruit interaction and its feasibility for various tomato cultivars were studied.

Finally, constructive aspects of ETR, integration and optimization of prehension and optical elements in a functional structure were presented.

In terms of technological maturity, the basic principles (TRL 1) were observed in [15] and [14]. Based on them, the technological concept of RADAR 00 (TRL 2) was formulated. The present work presents the proof of concept at the experimental level (TRL 3) and the validation of the components under laboratory conditions (TRL 4). Also, the RADAR 00 assembly was validated under relevant operating conditions in its own greenhouse, thus reaching the technological maturity level TRL 5.

8.2. Personal contributions

The theoretical and experimental research activity carried out in the framework of this doctoral training led to the realization of several personal contributions, some of which are structured in theoretical contributions, experimental contributions and industrially applicable contributions.

Theoretical contributions

- Design, application and interpretation of a questionnaire for the analysis of market requirements regarding the possibilities of using robotic systems in greenhouses. This achieved the secondary objectives OS1 and OS2.
- Critical analysis of the main prehension systems used in agriculture. This achieved the secondary objective of OS3.
- Development of an integrated conceptual model of ETR. This achieved the secondary objectives OS4, OS5, OS6.

Experimental contributions

- Analysis of market requirements regarding the possibilities of using robotic systems in greenhouses in the Western area of Romania
- Analysis of market requirements regarding the particularities of prehension elements used in greenhouses
- Design and functional optimization of a tomato harvesting RTE
- Determining an original solution for correct identification of ripe tomatoes. This contributes

to the achievement of the objective of OS4.
- Determining an optimal solution regarding the interaction between the gripper and ripe fruit. This contributes to the achievement of the OS5 objective.
- Realization of the original design of the robotic arm, which contributes to the achievement of the OS6 objective.
- The study of the dependencies between the average force applied, F and the gripping angle, U, the relative deformation ΔD_{rel}, the average height H_{med} and the average diameter D_{med} of tomatoes (formulas (7), (8), (9)).
- Determination of upper limits for the average pressing force in the case of 15 varieties and hybrids of tomatoes produced by SCDL Buzău, if the relative deformation of the fruits following the interaction with the gripper does not exceed a certain threshold value (0.1%, 0, 2% or 0.3%).
- Determination of upper limits for the average pressing force in San Marzano tomatoes when the relative deformation of ripe fruit at harvest is between 0.2% and 0.6%.

Contributions applicable in industry

- A practical solution for identifying ripe fruit, applicable within RTE
- A solution to move the robotic arm to pick a ripe fruit
- Solutions regarding the integration and optimization of ripe fruit identification systems and the interaction between gripper and fruit in a functional structure
- Establishing the tolerances used in the design, control and command of prehension systems
- Robotic technological equipment for picking tomatoes

8.3. Prospects for further research development

The RTE prototype developed for tomato harvesting – RADAR 00 – is a relatively cheap prototype and easy to maintain in terms of programming. It works in greenhouses where the environment is partially controlled, making it suitable for small-scale demonstrations.

From the point of view of technological maturity, the RADAR 00 concept reached TRL 5 maturity level. Procedurally following are activities to demonstrate the model in relevant operating conditions in the agricultural environment (TRL 6), demonstrate the prototype in relevant operating conditions (TRL 7), then its completion (TRL 8 and TRL 9).

An aspect that can be further developed is the extension of the gripper to pick other types of fruits and vegetables (eg yellow tomatoes, yellow peppers, cucumbers to be correctly identified, etc.).

Another aspect that will be improved in the future is the chassis and the distance between it and the ground (increased "ground clearance"). Thus, the prototype would be used in wider conditions in greenhouses. By using more powerful motors on the chassis, it becomes possible to attach a mini-trailer (basket) in which the harvested fruit can be stored immediately. Thus, the fruit picking time is significantly reduced.

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