Structured Design of a Novel End-Effector for a Bush Trimming Robot

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Abstract

The European TrimBot2020 project researches the robotics and vision technologies to prototype the first autonomous outdoor garden trimming robot. The robot navigates over different terrains, approaches boxwood plants and trims them to a desired shape. The robot platform is based on a modified Bosch robot lawnmower, which navigates autonomously using 3D-based vision scene analysis. During trimming a robotic arm is controlled by visual servo in order to trim the bush. A novel end-effector had to be designed to guarantee flexibility of the manipulator, precision of trimming and smoothness of the trimmed bush surface. This paper describes the structured design of this bush trimmer. When faced with a design problem with many interconnecting system elements, structured design is a tool to be used to iteratively and step by step guide the designers in making the right design choices at the right moment during the different design phases. First, preliminary research is done to analyse the problem and to assess the goals of the end-effector. Second, the functions are determined and working principles are found and put into a coherent structure. Finally, this leads to a composition of several preliminary designs of which the most promising one is determined. This design is built as a working prototype. Next to this, 3D-Computer Aided Design (CAD) tools and rapid prototyping is used to test ideas along the design process. The final design, based on contra-rotating blades, was discussed in terms of how and to what extent it has met the requirements, objectives and functions found during the structured design process. Moreover, the results of lab and field tests have shown the first functional results and points of improvements have been identified. A novel trimming method, by contra-rotating blades, has been found using structured design which meets the demands and limitations of other system components of the robot.

Keywords: robot, end-effector, structured design, bush trimming, mobile robot.

1. Introduction

In agriculture, robots and autonomous systems are nowadays utilized in more and more areas in for example grafting, packaging and harvesting of fruits, flowers and vegetables (Bac et al., 2014). Recently, for instance, the company Cerescon introduced an asparagus harvesting robot in the Netherlands (https://www.cerescon.com/NL/home) and the EU project Sweeper nears its completion of the sweet-pepper harvesting robot (http://www.sweeper-robot.eu/).

Nowadays, many people own a robotic lawnmower and thus automatic gardening has also raised the interest of companies and researchers on robotics, computer vision and artificial intelligence. In this paper, we present the development of an end-effector using structured design for a gardening robot that will allow the robot to trim bushes. It is currently under development in the EU project “Trimbot2020” (http://trimbot2020.webhosting.rug.nl/).

The TrimBot2020 project researches the robotics and vision technologies to prototype the first outdoor garden trimming robot. The robot will navigate over varying terrain, approach bushes and hedges to trim them to an ideal shape. The following European partners develop the vision soft- and hardware and control algorithms; University of Groningen (The Netherlands), University of Amsterdam (The Netherlands), University of Edinburgh (Scotland), Alberts-Ludwigs Unversitaet Freiburg (Germany) and the Eidgenoessische Technische Hochschule Zürich (Switzerland). The robot hardware; the robot carriage, manipulator, end-effectors and the control will be developed by: Robert Bosch GmbH (Germany) and Wageningen University & Research (The Netherlands). With that many partners, the broad scope of interests and varying requirements it is of key importance to structure the design process. In this paper the design methods are addressed to guide the process of designing the Trimbot end-effector. Secondly, the outcome will be presented with which the first laboratory and field tests were made. Third, the results are discuss and reflect back on the design of this first version of the end-effector.

2. Materials and Methods

Design methods

Systematic design, assists researchers in design choices, structures the design process and stimulates creativity. Systematic design methods include either process-based design methods or systems engineering methods. Examples of process-based methods are structured design (Siers, 2004) or engineering design (Cross, 2000). The use of these two methods turned out to be effective in previous research (Van Henten et al., 2006; Bakker, 2010; Nieuwenhuizen, 2009). Examples of systems engineering in agriculture is the determination of number of robot arms, multiple arm configuration, degrees-of-freedom, and horticulture workspace design (Edan, Miles, 1994).

Systematic design is the process of gradually developing the hardware and software components of a (robotic) system using information regarding needs of stakeholders, project objectives, requirements, functions, and working principles. Systematic design assures that a decision for a certain design is not just based on technical trade-offs, but also matches project objectives, project requirements, and needs of stakeholders. Definition of the requirements is a critical step in systematic design. In horticulture an end-effector must deal with varying shapes and sizes which might be taken care of using a dexterous or anthropomorphic hand. But on the other side, due to the hostile environment, the frequency of operation and the low market potential for robots in horticulture which drives the need for cheap solutions this dexterity must not be solved using a complex mechanism with a lot of moving parts, (Bac, 2014). The challenge is to find a low-cost, robust, simple and above all elegant design that ensures dexterity with a minimum of moving parts. The end-effector design problem must be thorough analysed to come up with the simplest solution. According to (Edan, 2000) for horticultural end-effectors, "the feasibility of the design concept can only be evaluated in field conditions under actual operating conditions".

Structured design

The design method used in this paper is based on structured design (Siers, 2004) and the first phase (out of three in total) of Reflexive Interactive Design (RIO in Dutch), (Bos, 2010). The first steps in RIO include a thorough analysis of the problem by listing the key challenges, actors, literature research and establishing the brief of requirements (BOR) (Figure 37, left). The second phase is based on structured design from which step three to five are used (Figure 37, right). Step one and two of structured design more or less coincide with step one, two and three of RIO. The structured design method is detailed in (Figure 38). This method is divided in five steps, starting with a preliminary research, problem definition, assessment of working principles, design, shaping and realization.

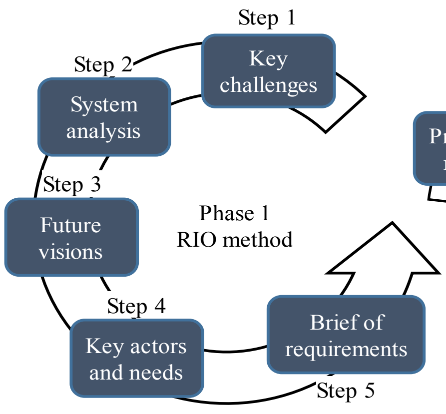

Figure 37. Graphical overview of the first phase of the RIO method. Hereafter, in phase 2, the methodical design method is used. Each phase consists of different steps (Bos, 2010).

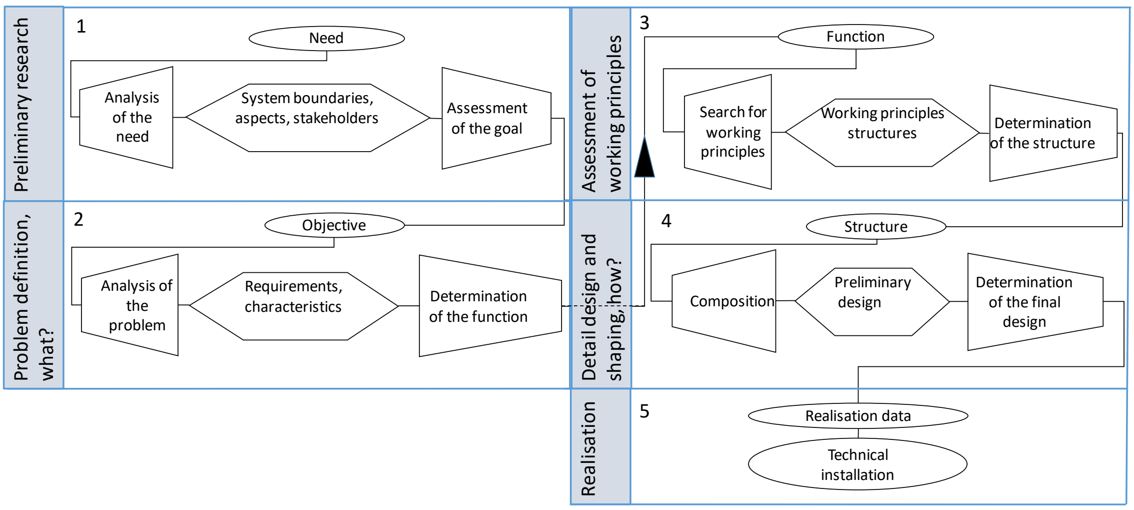

Figure 38. Overview of the five steps in structured design of Van den Kroonenberg. Adapted from (Siers, 2004).

Each step in both design techniques consists of the same structure. First, it starts with an input followed by a diverging stage then an arrangement stage and finally a converging stage from which we draw conclusions, Figure 38. The result of one step is the input of the next step. Furthermore, the results of each step are not definitive and the development is an iterative method. For example, if a key function is missing during the development of concepts, this step will be adapted to make sure the solution space remains open for alterations. Due to the compactness of the article the description of all steps is not possible. We will discuss the most important findings, conclusions and discussions.

3. Results and Discussion

Determining needs, functions and requirements of the Trimbot end-effector

Determining the Key challenges

The first step of the RIO method is to determine the key challenges in the design of the Trimbot end-effector. The following drawing shows which system elements contribute to this process, Figure 39. The key challenges describe what the end-effector must do in order to have a successful demonstration at the end of the Trimbot project. The description of the key challenges is used to derive the functions of the end-effector and consequently their attributes described in terms of requirements (fixed or variable), demands and wishes.

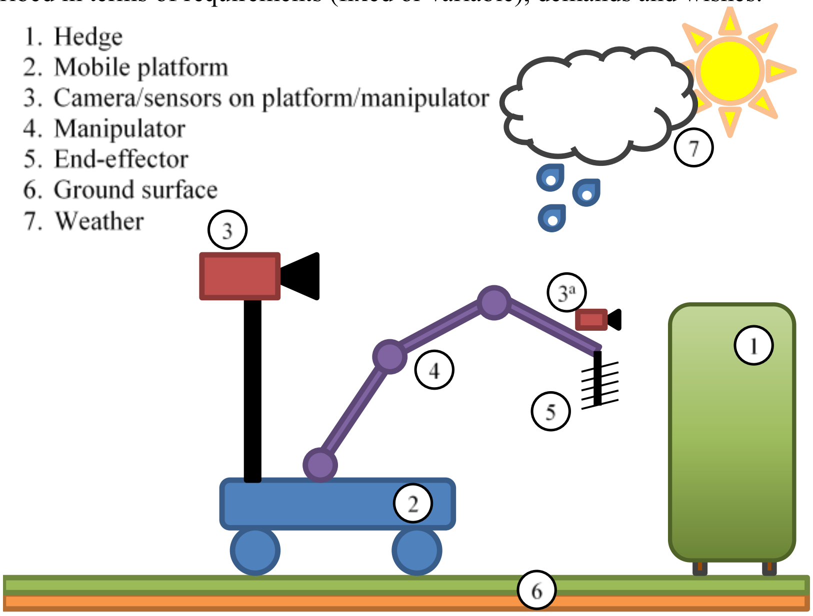

Figure 39. System elements of Trimbot which might contribute in terms of key challenges to design the end-effector.

The given system elements are used to derive the key challenges by analysing the following:

- What is the influence of element X on the Trimbot end-effector.
- How does this relate to the functions, behaviour and needs of the Trimbot end-effector.

Before we enter into this process the following demarks the design of the Trimbot end-effector and determines at a basic level what will be excluded from the design process:

- The aim is to design and build the Trimbot end-effector up to Technology Readiness Level (TRL) 5-6. Meaning, to build a prototype ready for testing in its relevant environment.
- Safety for the human end-user is not incorporated in the design of the Trimbot end-effector.
- The focus is on the design of the trimming tool. All other elements are outside the scope of our project.
- Engineering for cost-effective manufacturing is also outside the scope of the project.

Overall Key challenge and challenges related to system elements

The following key challenge was found analysing the description of work of the Trimbot 2020 EU proposal. "To design a trimming tool for an outdoor hedge and bush trimming robot for demonstration purposes, which can carried by a six degree of freedom manipulator to trim hedges and bushes to their, to be specified, shape by converting information given by the sensor system mounted on the end-effector into a desired action of the end-effector". Below some challenges of the end-effector that are based on the system elements are listed:

- Weather conditions: design an end-effector which is able to withstand different weather conditions and is able to perform well in different outdoor weather conditions (Sun, rain, wind, etc.).

- Sensor system & plant model: within the "limited" set of representations (line, surface) of the garden elements given by the sensor system, the trimming tool must be able to be orientated and positioned by the manipulator and to follow this set of representations.
- To design the right combination of end-effector and robotic arm (mechanism, size, accuracy) given the properties of the sensor system (accuracy, detail level).
- Given a defined quality from the plant model, controlled/measured by the sensor system, the manipulator will position and orientate the end-effector to a predefined point with a certain accuracy and then follows a succession of connected paths along a given line. The end-effector must perform its task along that path within the desired quality and within the reach of the robotic arm.
- During garden travel, the end-effector must not destabilize the platform and prevent branches from getting stuck.
- The end-effector should be able to trim with a predefined quality and accuracy based on predefined specifications, (see Table 16).

With these key challenges and the system elements in mind we are now able to conduct a system analysis.

System analysis

In order to visualize and understand the system, the Trimbot system is analysed from the description of work EU document. This gives insight in the problems/challenges and which functions needs to be performed in order to trim a bush autonomously and have a successful demonstration at the end of the project. Below a short overview of the different functions are given (Table 15) and one level is drawn in function blocks in Figure 40. In the end a complete function block diagram was made for the total system which at a later stage helped to design the control software for the Trimbot.

Table 15. Partial overview of functions and their sub-functions of the Trimbot system.

1. Mapping of garden	2. Calculate trimming actions	3. Execute trimming actions
1.1. Observe garden (acquire data)	2.1. Combine semantic data with plant model	3.1. Navigate to next waypoint
1.2. Fusion of missing data	2.2. Calculate ideal shape of each object	3.2. Execute trimming/clipping action 3.2.1. Move end-effector to desired position and orientation 3.2.2. Move end-effector along the path 3.2.3. Give feedback on trimming quality
1.3. Mapping of data	2.3. Calculate trimming/clipping path for tool	3.3. Execute waste handling
1.4. Semantic segmentation of data	2.4. Calculate driving path with waypoints for vehicle	

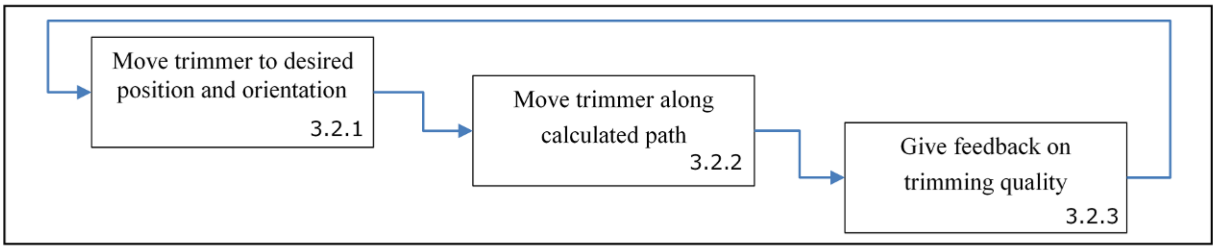

Figure 40. State machine function block of level 3.2 (execute trimming actions level 3).

Key Actors & Needs

The purpose of this design step is to define the actors and their needs which play a role in the problem. This prevents the product of being based on only one actor. After identifying the actors, their viewpoint on the problem and their basic needs are being investigated. This ensures no viewpoints are missed during the design.

- Potential manufacturer
  - Attractive product for customers.
  - Explore and utilize new markets.
  - Low-cost and safe tool to trim bushes.
- European Union
  - Induce technical development.
  - To stimulate cooperation between universities and private companies.

- A successful demonstration of the system resulting in a positive exploitation of the end results.
- Research groups vision
  - A stable mechanism to mount camera's, sensors and lighting systems.
  - An unimpeded view from the camera's, sensors mounted on the end-effector towards the bush.
- Research groups modelling and control
  - Stable and predictable sensor information from the camera's and sensors mounted on the end-effector.
  - To easily convert that information into trimming actions which are executed as predicted.
- Research groups trimming operations
  - Use information about location and ideal trimming path to execute the trimming action.
  - Development of a computer controlled end-effector.
  - Development of a robot arm with visual servoing to enable the end-effector to perform its task.
- Visitors, demonstration and dissemination
  - Properly working machine.
  - High technological level.

Brief of Requirements

Based on the key challenges and the needs of the key actors, a Brief Of Requirements (BOR) is constructed. In Table 16, for each component a set of requirements is stated. This gives the total of the design constraints in which solutions should be found. The fixed requirements should always be met and the variable requirements have a certain range. During the later design step, different technical solutions will be reviewed using this BOR.

Table 16. Brief of requirements (BOR) related to end-effector design (this is not the complete BOR).

nr.	Component	Requirements	fixed	var-iable	desi-rable	target	min. value	max. value	unit
1	Common requirements	The system should be able to operate autonomously.	x						
2		The system should be able to handle a relative humidity of 90%.		x		95	90	100	RH %
3		The system should be able to operate during sun-radiation of 1000W/m2		x		1200	1000	1200	W/m2
4		The system should be able to handle at least 5mm/h rain			x	15	5	-	mm/h
5	Robotic arm	The robotic arm should move without damaging the plant while reaching its desired position.	x						
6		The robotic arm should be able to position and to orientate the trimmer as required	x						
7		The robotic arm should be able to withstand the reaction forces during cutting.		x		25	20	50	N
8		The robotic arm should be able to bring the tool to a height of at least 0.6 meter.		x		0.8	0.6	-	m
9		The robotic arm should be able to bring the tool 0.05 meter from the ground surface		x		0	0	0.05	m
10		The robotic arm should have a accuracy of at least 5mm at the desired point.		x		0	0	5	mm
11		The robotic arm should have accuracy of at least 5mm while following a path.		x		0	0	5	mm
12		The robotic arm should have a payload of at least 2 kg		x		3	2	10	kg
13		The robotic arm should be able to operate on a low voltage DC power supply			x	12	6	24	V DC
14	Hedge trimming tool	The trimming tool should not harm other branches (touching is ok).	x						
15		The trimming tool should be able to cut hedges, spheres, cubes, cones, pyramids and variations thereof.	x						
16		The trimming tool should be able to cut surfaces with an accuracy lower than 5mm.		x		2	0	5	mm
17		The trimming tool should be able to cut hedges with branches of at least a diameter of 4mm .		x		4	4	-	mm
18		The trimming tool should be lighter than 2 kg.		x		0.25	0	1	kg
19		The trimming tool should be able to cut at least 2 m2 per hour.		x		5	2	10	m2/hour
20		The trimming tool should be autonomous interchangeable within 3 minutes .			x	1.5	0	3	min
21		The trimming tool should be able to measure the surface orientation and position (according to the plant model)			x				
22	Both robotic arm & tool	The combination of robotic arm and tool hould be able to cut the desired hedges and roses.	x						
23		The system should be able to cut hedges with a height of 0.5 meter.		x		0.9	0.5	-	m
24		The system should be able to cut hedges with a depth of 0.5 meter.		x		0.9	0.5	-	m

Preliminary research, evaluation of State-of-the-art in consumer and professional hedge trimmers

A comprehensive research is done in current state-of-the-art on bush trimming tools. Based on that, different designs are evaluated. In Figure 41 left, examples are shown of a motorized and a manual trimming tool. Motorized trimmers usually consist out of two blades of which one is usually stationary where a second moves over the stationary blade. Manual trimmers have a scissor type of configuration in which the blade length varies (Figure 41, second picture). The blades of professional trimmers, Figure 41 right, move both in opposite directions to provide a higher cut capacity. Most professional trimming tools are not easy adjustable for different plant shapes. Adaptability or flexibility is an important requirement for Trimbot.

Figure 41. some examples of manual garden trimming tools, (first two pictures left) and professional trimming tools (last two pictures right).

Problem definition, evaluation of hedge trimmers in regards to the system element “manipulator”

The way the manipulator is intend to be controlled has an impact on the configuration of the end-effector and vice versa. From early on, the actors of the research group “modelling and control” expressed their need that the end-effector should ideally be used as a milling type cutter. That means that the last axis of the manipulator should coincide with the rotation axis of the hedge trimmer, Figure 42 left. In that way, the joint control of the manipulator resembles computer numerical control (CNC) as is used in 6 axis CNC milling machines.

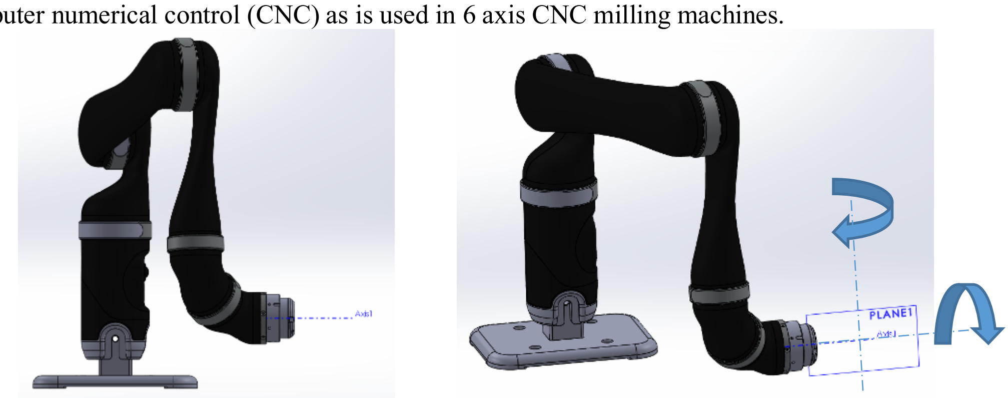

Figure 42. Left; last axis of the manipulator (Kinova Jaco 2 manipulator 6 degrees of freedom, Kinova, Boisbriand, Canada), coincides with the trimming tool. Right; a planar tool would add two degrees of freedom to control.

Using a planar like tool configuration, as shown in Figure 42 right, would add two more degrees of freedom to control by the manipulator. In that sense, coinciding axes offer benefits to solve more easily the joint control in mathematical terms. From that follows, using the idea of coinciding axes a circular knife would be a logical choice.

Working principles and structures

As shown in Figure 43, a morphologic chart has been made in order to evaluate the solution space for the design for the end-effector. For each function needed to fulfil the trimming task, different solutions (called concepts) have been explored. Also concepts from other fields (not agricultural) are evaluated, like cutting with heat, laser or high pressured water jets. The following examples of functions are evaluated (not a complete overview):

Method of separating a branch: concepts to separate the unwanted part of the branch

Configuration of sets of knives: if multiple knifes are used, ideas are found of how they are moved relative to each other. If a single knife is used, single is chosen.

Configuration to the branch: methods of how the knife(s) is/are applied relative to the branch.

Movement of knife: if a double blade is chosen, how the cutting blade moves relative to the contra-blade.

Energy supply: method of applying the force needed to perform the cutting task.

After all concepts were inserted in the chart, multiple design lines were drawn, by choosing one concept for each function. The performance of those design lines have been discussed with the key actors and some iterations to the concepts choices have been made to come to the final design solution. This final design line for the end-effector related to the method of cutting (in red) is drawn in Figure 43.

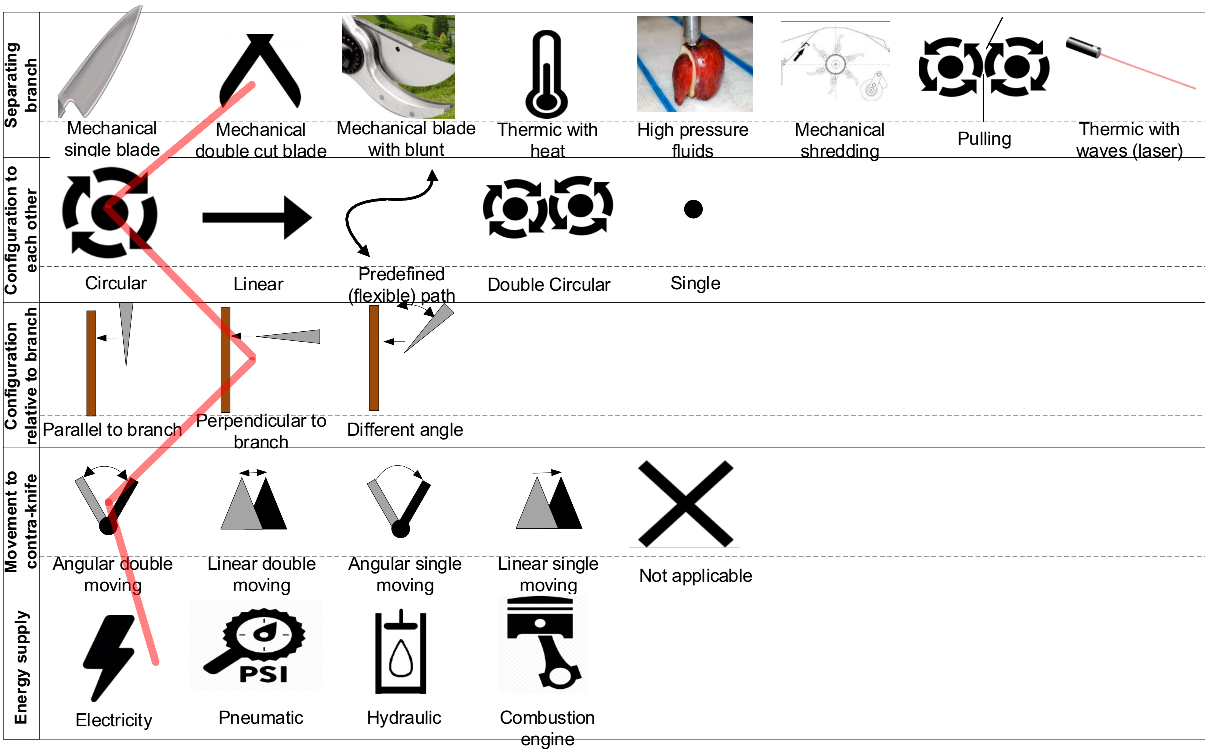

Figure 43. Morphological chart of working principles related to functions of the end-effector.

Detailed design and first realisation of the Trimbot end-effector

Summarizing the design steps of former paragraphs led to the most promising idea to have a circular knife configuration which axis coincides with the last axis of the manipulator. Because professional hedge trimmers, with linear knifes moving both in opposites directions, are successful in cutting branches in one movement, that particular mechanical configuration will be copied. This idea results in two circular counter rotating sets of knifes. One of these will have sharp edges whereas the other will act as an anvil with blunt edges. To enable the counter rotating movement of the end-effector blades we choose to buy an existing power tool (made by Powerplus tools, Lier, Belgium) that had that feature build in. This machine was stripped down so that the gearbox could be used in the design as presented in Figure 44. Furthermore, the original 230V motor is replaced by a 24V DC servo motor and control. This enables us to monitor the motor current and speed and provides the Trimbot platform to start and stop the end-effector using simple IO commands. The total weight is 2.1 kilograms and the motor and gear is protected by a 3D printed housing with embedded rubber seals to protect it from dust and rain and to give it an aesthetic look. Flat surfaces on the side and on top of the gear housing will provide space to mount camera's, sensors and or lighting systems (during this point in the project it was still under discussion what camera or sensor systems to use). The end-effector is mounted on the manipulator using 6 screws providing a quick way to swap the tool if needed. The first design looks as follows, Figure 44.

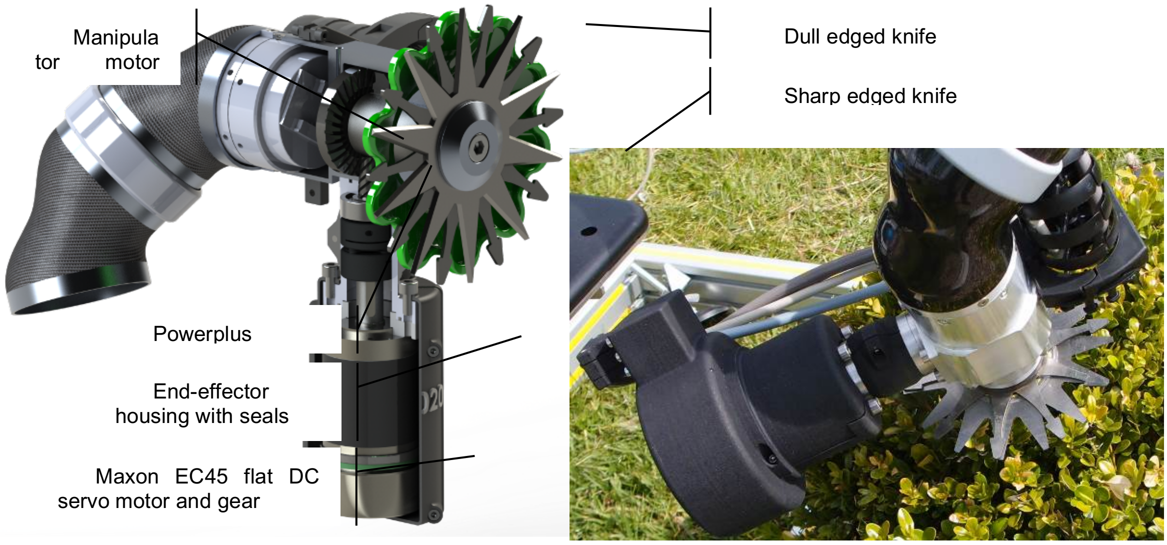

Figure 44. Cross section view (left) and the end-effector mounted on the manipulator during a first field test (right).

Final results

The manipulator with end-effector was mounted on a rig with a bush in front of it placed on a turn table to provide full access to the bush from all sides, Figure 45 left. Cameras were mounted on top of the end-effector to provide feedback of the initial position of the manipulator. The rotational speed of the blades was chosen by reviewing the resulting quality of the cut which turned out to operate best at 180 rpm. Next to that, the lab trail proved that the end-effector could easily cut through all the branches, Figure 45, right.

Figure 45. left; end-effector mounted on the manipulator during a lab test. The bush is set on a rotation table to provide access from all sides. Middle; bush before trimming and after trimming; right.

Discussion

The total system should be able, according to the BOR (Table 16), to trim the surface within +/- 5 mm. Currently, the first evaluation (not presented in this paper) revealed that the system is not able to achieve this goal. Although many factors beside the end-effector design contribute to this, four are related to the end-effector design. First, the weight of the cables to power and control the DC servo motor of the end-effector were not taken into account during the design process. This ads 2 more kilograms to the configuration. The manipulator itself is designed to aid people with a disability and is not rigid enough to keep a high positioning accuracy with this extra weight. It therefore deforms and cannot follow the path within the desired limits given by the manipulator controller. Second, the motion planning strategy assumed an isotropic outgrowth of the braches of the bush (from the centre of the bush growing outwards) while in reality the braches grow anisotropic (from the base of the plant upwards towards the light). The design team currently thinks that the performance could improve if we take that into account into the motion planning of the manipulator. How to address this is still under discussion, a first idea is to plan the motion beginning at the base of the plant and then to move upwards to the top and to trim the bush in the direction of the branches. Third, the motor mounted directly underneath the tool obstructs the manipulator from getting at the lower parts of the plants. We have advised the key actor from the motion control group to add a constraint in the cost function of the last manipulator joint to turn the motor upwards while cutting near the ground surface. And finally, the camera housing and the position should be revised. Its current design, which was quickly added to the system at the last moment, is mechanically not sufficiently rigid. In the next few months leading to the field test during the summer of 2018 these problems will be addressed. The mass will be lowered by providing extra mounting points of the cables along the manipulator to distribute the weight, mount the motor at one of the joints of the manipulator and drive the blades using a flexible shaft. And finally, an integrated camera/sensor housing will be added to the end-effector that better protects the cameras and prevents the cameras from changing their mounting pose due to mechanical impact as requested by the vision group.

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