TrimBot2020 Deliverable D2.1

State-of-the-art, progress beyond, and system design for mechatronics, motion planning and vision-based replanning

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Dissemination: CO

Abstract: This document presents the mechatronic design of the robot, as well as the design of the motion planning software for the trimming action. The mechatronic design entails the requirements definition and the selection/construction of the robot arm, the trimming tool and the interface among the arm and the mobile platform. The design of the motion planning software builds upon the review of the literature about coverage-aware motion planning and vision-based replanning.

Deliverable due: Month 12

Contents

1 Robot arm

In order to position and orientate the bush and hedge trimming and rose cutting tools of the Trimbot2020 robot, a robotic arm will be used. In the table below the requirements needed to perform the tasks have been listed. Based on that table the most suitable arm was selected.

1.1 Requirements

Based on a thorough system analysis a list of challenges, key actors and main functions of the project are made. First research is done to the current situation and the problem. Based on the key actors and their needs a list of requirements for the robotic arm is made:

Table 1: Overview of the robotic arm requirements (F=fixed, V=variable, W=wish)

Requirement	Type	Target	Min. value	Max. value	Unit
The robotic arm should move without damaging the plant while reaching its desired position.	F				
The robotic arm should move without moving the hedge while trimming it.	F				
The robotic arm should have a smooth exterior, in order to prevent branches from getting stuck.	F				
The robotic arm should be configured in a way that it is able to position and to orientate the trimmer as required.	F				
The robotic arm should be ROS compatable	F				
The robotic arm should be able to withstand the reaction forces during cutting.	V	25	20	50	N
The robotic arm including control box should be lighter than 20 kilo.	V	10	0	20	kg
The robotic arm should have a low center of mass during navigation.	V				kgm2
The robotic arm should have a low center of mass during trimming/clipping.	V				kgm2
The robotic arm should have at least 6 degrees of freedom .	V	6	6	9	Number
The robotic arm should be able to bring the tool to a height of at least 0.6 meter.	V	0.8	0.6	-	m
The robotic arm should be able to bring the tool 0.05 meter from the ground surface	V	0	0	0.05	m
The robotic arm should have a reach of minimal 0.6 (1/2xindigowidth+1/2+widthbush+0.1m extra) meter at a height of 0.5 meter	V	0.7	0.5	1	m
The robotic arm should have a accuracy of at least 5mm at the desired point.	V	0	0	5	mm
The robotic arm should have accuracy of at least 5mm while following a path.	V	0	0	5	mm
The robotic arm should have a payload of at least 2 kg	V	3	2	10	kg
The robotic arme should have a power consumption of less than 250 Watt	V	150	0	250	W
The robotic arm have a solid particle protection of at least 5 (Dust protected).	W	6	5	6	IP-rating
The robotic arm should have a liquid ingress protection of at least 5 (light water jets).	W	6	5	9	IP-rating
The robotic arm should be able to operate on a low voltage DC power supply	W	12	6	24	V DC

1.2 State-of-the-art

Following the requirements, an extensive research was conducted to evaluate different robotic arms. Only robots commercially available were considered. Due to the requirement the system has to have at least 6 degrees of freedom (DOF), only these arms were taken into account. There are different types of robotic arms, however only arms of the type articulate robot arm seemed to match the requirement to have at least 6 degrees of freedom. As a result, only articulated robot arms were evaluated. Furthermore the search was limited to ROS compatible arms. Most industrial type robotic arms fall off due to their high weight. Also some robotic arms were not released for sale in the coming year, so also not applicable as an option for this project. Three robotic arms met the requirements and were investigated more extensively. In the following, a description of them is provided.

1.2.1 Kinova Jaco2

The Kinova Jaco2 is a robotic arm developed primary for persons with a disability. Its links are made from carbon fiber and due to that the weight is 4.4kg only. It has a horizontal reach

Figure 1: Side view of the kinova Jaco2 arm.

Figure 2: Schunk Powerball LWA4B arm.

of 760mm, which meets the requirements. Rotations per joint are limited by software and are set to 27.7 turns. Its payload is limited to 2.2kg. Furthermore the maximum speed is with 36deg/s slower than the speed of the other two arms considered. Moreover, the positioning repeatability is 3mm, what is considerably lower than the other two arms but still within the defined requirements.

1.2.2 Schunk Powerball LWA 4P

The arm Schunk Powerball LWA 4P is designed as a lightweight 6 DOF arm. It uses 3 balls with each 2 joints integrated. That results in 6 DOF. Its payload is 6kg (rather high with respect to our requirements) and the repeatability is 0.15mm. Furthermore its speed is 72deg/s more than sufficient for our application. It has an average ability to rotate 350 degrees per joint. Also the horizontal reach is with 730mm which is within the requirements. The total weight of this arm is 15 kg.

1.2.3 Schunk Dextrous LWA 4D

The weight of this arm is the highest with 16kg. It has 7 degrees of freedom and a repeatability of 0.15mm. Its reach in the horizontal plane is the smallest of the 3 arms compared. This is due to the length of link 1. The power consumption is also the highest. Furthermore a downside is that this arm has the highest price of the 3 arms compared.

1.3 Evaluation

1.3.1 3D reachability analysis

Since all three options meet the requirements, an extended evaluation was done which would fit this project the best. First of all, an evaluation of reachability was made in 3D space. As shown

Figure 3: Schunk Dextrous LWA 4D arm.

in Figure 4, the reachability of the arm and platform is studied using a 3D program to gain insight in the working space of the arm. Based on the manufacturer specs, the LWA4D should have the highest reachability. However in simulation this arm resulted in the worst reachability, due to the large distance between the base and link 2. In the end it was concluded that the reachability of the Jaco2 arm was most suitable for our target application.

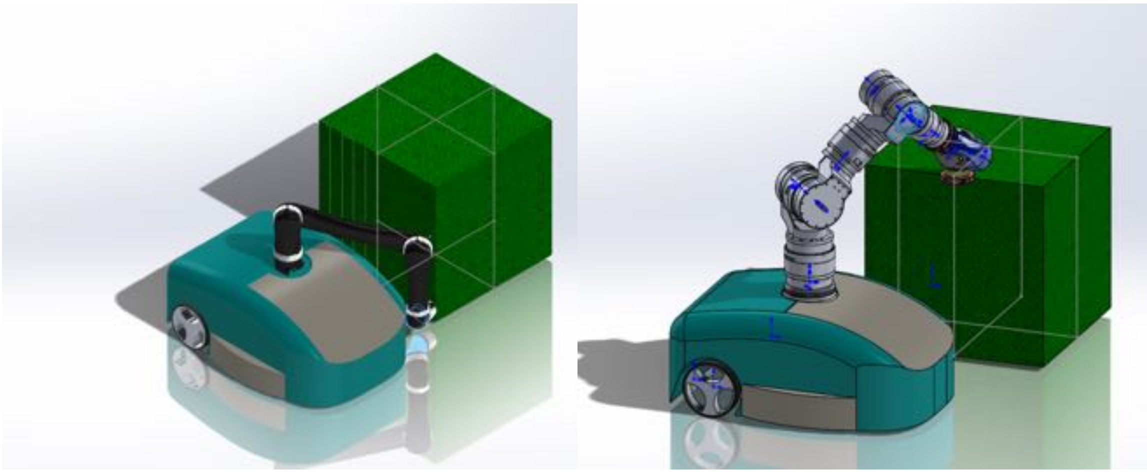

Figure 4: Left: 3D simulation of the reachability of the Kinova Jaco2 arm. Right: 3D simulation of the reachability of the Schunk LWA4D arm

1.3.2 Other characteristics

A thorough investigation was done to other characteristics and ROS compatibility. Also performance of the real hardware was evaluated during practical experiments. During a project meeting, most important characteristics were determined and the definitive choice was made. The biggest drawbacks of the Schunk LWA4D are its weight and reachability. Furthermore, it was by far the most expensive arm. The extra degree of freedom is not needed in the project. The Schunk LWA4P is very fast and accurate, but limited in reachability and weight. The Kinova Jaco2 has best reachability and power consumption but is by far not as accurate. However, it is decided that repeatability could be increased with visual servo feedback. Furthermore the reachability of 3mm would be enough for the project. The speed is high enough for cutting and the biggest advantage was the low weight. Since a lot of other components have to be carried by the platform, every reduction in weight is a benefit. However, some adjustments to the arm have been made in cooperation with its supplier. First of all, an upgrade to the protection level

Table 2: Schematic overview of the characteristics of theSchunk Powerball LWA 4P robotic arms which meet the requirements. Characteristics are colored relatively how the score in comparison to each other. The best value for a single characteristic gets the light green color; the worst value of the three gets a light red value and the value in-between a combination of the two (more close to the best, more green, and closer to the worst more red)

Characteristics:	Unit	Kinova Jaco	Schunk Powerball LWA4P	Schunk Dextrous LWA4D
Weight robot:	[kg]	4.4	15	16
Weight controller	[kg]	0	0	0
payload	[kg]	2.2	6	10
Reach(first joint to tool cente	[mm]	900	650	1100
average joint range	[±°]	9972	168	160
Average speed per joint	[deg/	36	72	65
Repeatability	[mm]	3	0.15	0.15
Footprint diameter	[mm]	41	140	140
Degrees of freedom	[-]	6	6	7
Control box size	[mm³	no control box	no control box	no control box
IP	[-]	20	40	54
Power consumption	[W]	50	72	120
Material	[-]	Carbon + aluminum	Plastic +aluminium	Plastic +aluminium
min power supply	[V]	18	24	24
distance ground to tcp	[mm]	1038	880	1100
distance first axle to tcp	[mm]	880	780	890
max distance horizontal	[mm]	760	730	720
ROS compatable	[-]	yes	Yes	yes
3d reachability analysis	[-]	1	2	3
price	[€]	27365	30000	60000

against dust and water is made. The supplier has agreed to protect most valuable component by adding better seals and protect electrical components with extra sealant. Furthermore an update on the ROS driver was announced by the company that should solve current issues with the driver.

Table 3: List of the requirements of the bush trimming tool (F=fixed, V=variable, W=wish)

requirement	Type	target	min. value	max. value	unit
The trimming tool should not harm left branches	F				
The trimming tool should be able to trim surfaces	F				
The trimming tool should be able to cut hedges, spheres, cubes, cones, pyramids and variations thereof.	F				
The trimming tool should be able to trim different plant types, boxwood and ivy	F				
The cutting surface of the branches should be smooth (no visible frays)	F				
The trimming tool should stop immediately in case of an emergency stop	F				
The trimming tool should get stuck in less than 1% of the to be cutted branches.	V	0	1		%
The trimming tool should be able to cut surfaces with a accuracy of less than 5mm (length between the longest and shortest cutted branch	V	2	0	5	mm
The trimming tool should be able to cut hedges with branches of at least a diameter of 4mm .	V	4	4	-	mm
The trimming tool should consume less than 20 Watt	V	0	0	20	W
The trimming tool should be lighter than 1kg.	V	0.25	0	1	kg
The trimming tool should have a solid particle protection of at least 5 (Dust protected).	V	6	5	6	IP-rating
The trimming tool should have a liquid ingress protection of at least 5 (light water jets).	V	6	5	9	IP-rating
The trimming tool should be able to cut at least a surface of 2 m2 per hour.	V	5	2	10	m2/hour
The trimming tool should be able to cut at least 5cm of outgrowth	V	8	5	10	cm
The trimming tool should be able to reach 98% of the to be cutted surface	V	99	98	100	%
The trimming tool should be interchangeable within 15 minutes	V	3	0	15	min
The trimming tool should be autonomous interchangeable within 3 minutes .	W	1.5	0	3	min
The trimming tool should be able to measure the distribution of the length of branches after cutting	W				
The trimming tool should be able to measure the surface orientation and position (according to the plant model	W				
The trimming tool is able to collect and remove the cutted pieces	W				

Table 4: List of the requirements of the rose cutting tool (F=fixed, V=variable, W=wish)

requirement	Type	target	min. value	max. value	unit
The clipping tool should not harm other branches (touching is ok), while reaching the desired branch.	F				
The clipping tool should be able to clip the Rose on individual level.	F				
The trimming tool should stop immediately in case of an emergency stop	F				
The clipping tool should be able to cut branches with a accuracy better than 10mm.	V	0	0	10	mm
The clipping tool should be able to cut at least 10 branches per hour.	V	25	10	50	[Nr]/H
The clipping tool should be able to cut branches with a diameter of at least 10mm.	V	10	10	25	mm
The clipping tool should consume less than 20 Watt.	V	0	0	20	Watt
The clipping tool should be lighter than 1kg.	V	0.25	0	1	kg
The clipping tool have a solid particle protection of at least 5 (Dust protected).	V	6	5	6	IP-rating
The clipping tool should have a liquid ingress protection of at least 5 (light water jets).	V	6	5	9	IP-rating
The clipping tool should be interchangeable autonomous within 3 minutes .	W	1.5	0	3	min
The trimming tool should be able to measure the location of where the branch has been cut with an accuracy of at least 10mm	W	5	0	10	mm
The clipping tool is able to transport the cutted branch	W				
The clipping tool is able to cut the branch with a cutting angle relative to the branche	W				

2 Trimming tools

2.1 Requirements

Based on a thorough system analysis a list of challenges, key actors and main functions of the project task were made. Based on those elements, a list of requirements was made. This was done for the bush trimming tool and the rose cutting tool separately, since they have different requirements. The requirements on the bush trimming tool (surface trimming tool) can be found in Figure 3. The list of the requirements of the rose cutting tool can be found in Figure 4.

2.2 Bush and hedge trimmers

2.2.1 State-of-the-art

A comprehensive research is done on current state-of-the-art on bush trimming tools. Based on that, different methods for the design are evaluated and a final design is chosen. In Figure 5, 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. The blades of professional trimmers move both in opposite direction to provide a higher cut capacity. Manual trimmers have a scissor type of configuration in which the blade length varies. Examples of manual trimming tools are shown in Figure 5. Figure 6 shows examples of professional trimming tools.

Figure 5: Two examples of manual bush and hedge trimming tools

Figure 6: Two examples of professional bush trimming tools

2.2.2 Evaluation

2.2.3 Tool configuration and manipulator control

The mechanical configuration of the bush trimming tool should ideally be used as a milling type of cutter. That means that the last axis of the manipulator should coincide with the rotation axis of the bush trimmer, Figure 7 left. In that way, the joint control of the manipulator resembles a CNC control (the same is used in 6 axis CNC milling machines).

Figure 7: Left: last axis of manipulator coincides with trimming tool. Right: a planar tool would add two degrees of freedom to control

The use of a planar like tool configuration, as shown in Figure 7 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. Following, using the idea of coinciding axes a circular knife would be a logical choice.

2.2.4 Knife configuration and manipulator control

Consumer type trimmers have the benefit that their action can be directly reviewed by their human operators. Speaking from the authors experience, to get a desired trimming result (in depth and evenness) usually the tool needs to be applied two to three times over the same spot on a bush. The human operator constantly reviews the result and controls the force, angle and speed of the trimmer along the bush surface. At this point in the Trimbot project we do not have the luxury of such feedback control. Ideally, the trimmer should get the desired job done in one pass without the need of above mentioned feedback control. The reason why consumer type trimmers are not suited is because their mechanical make up. Those trimmers make use of a stationary knife along which a second knife moves in parallel. This stationary part pushes about a third of the branches away and prevents them to be cut in a single pass, see Figure 8.

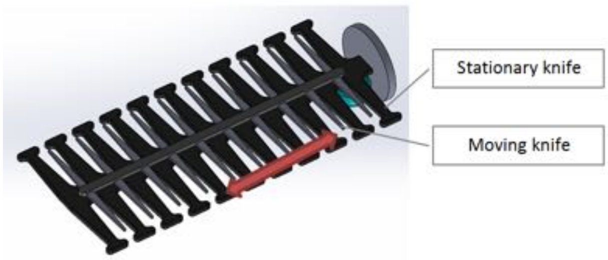

Figure 8: Mechanical principle of commercial bush trimmer

In contrast, professional trimmers, shown in Figure 6, move both knifes which allow almost all branches to be cut in a single movement. As shown in Figure 9, a morphological chart has been made in order to evaluate the solution space for the design, both for the rose clipping tool and the bush trimming tool. Since both have to perform the same function, the same chart is used for both solutions. For each function needed to fulfill 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 pressure. The following functions are evaluated:

2.2.5 Concluding evaluation

Summarizing the evaluation of the last two paragraphs led to the idea to have a circular knife configuration which axis coincides with the last axis of the manipulator. Because professional bush trimmers, with linear knifes moving both in opposite directions, are successful in cutting branches in one movement, that particular mechanical configuration will be selected in the design. This idea results in two circular counter rotating knifes. One of these will have sharp edges whereas the other will act as an anvil with blunt edges.

To power these knifes a servo control will be used. This will enable us to monitor and control the motor current which might be important to set the right rotational knife speed in relation to the speed of the manipulator. Next to that, it will be relatively simple to prove the control signals like start, stop and task done to the Trimbot control system.

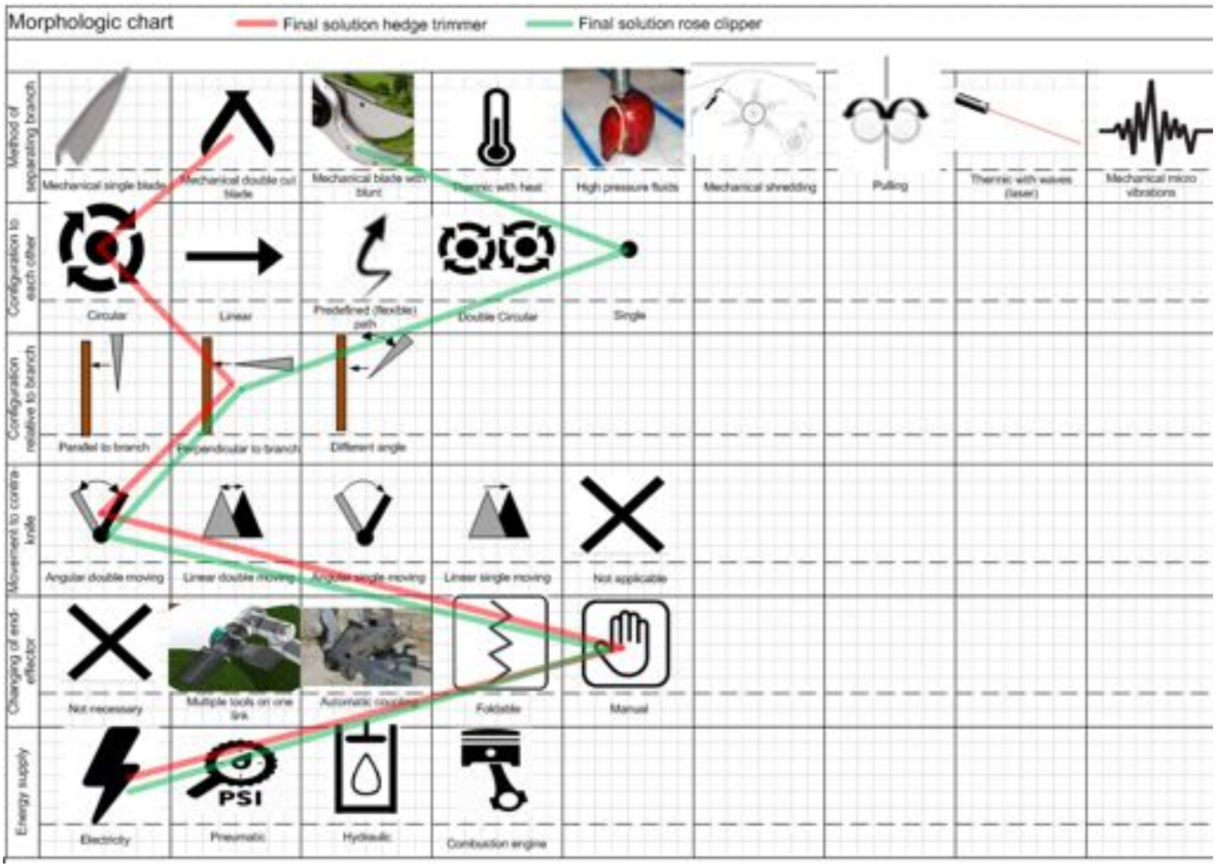

Figure 9: Overview of the morphological chart used in the design process. The red line indicates the components used for the final bush trimmer design and the green line represents the elements used for the rose clipper design.

2.2.6 Design

To enable the counter rotating movement of the trimmer blades, we chose to buy an existing power tool that had that feature build in. http://www.powerplus.net/6244/323836/circular-saws/powx0680-dual-saw-1050w-125mm.aspx This machine was stripped down so that the gearbox could be used in the design as presented in Figure 10. Furthermore, the original 230V motor is replaced by a 24 V DC servo motor and control. This enables to monitor the motor current and speed and provides the Trimbot platform to start and stop the bush trimmer using simple IO commands.

2.3 Rose trimmers an cutters

2.3.1 State-of-the-art

Roses come in a lot of varieties. From small, springy type of branches measuring 1 to 2 mm in diameter which grow to about half a meter in height to stern bushes with branches of 10 mm thick growing several meters tall. The first type can be trimmed with the same type of trimmer used for buxus or ivy. The latter are trimmed by removing individual braches using a scissor type of cutter. Electric cutters are provided for the semi-professional market, see Figure 11.

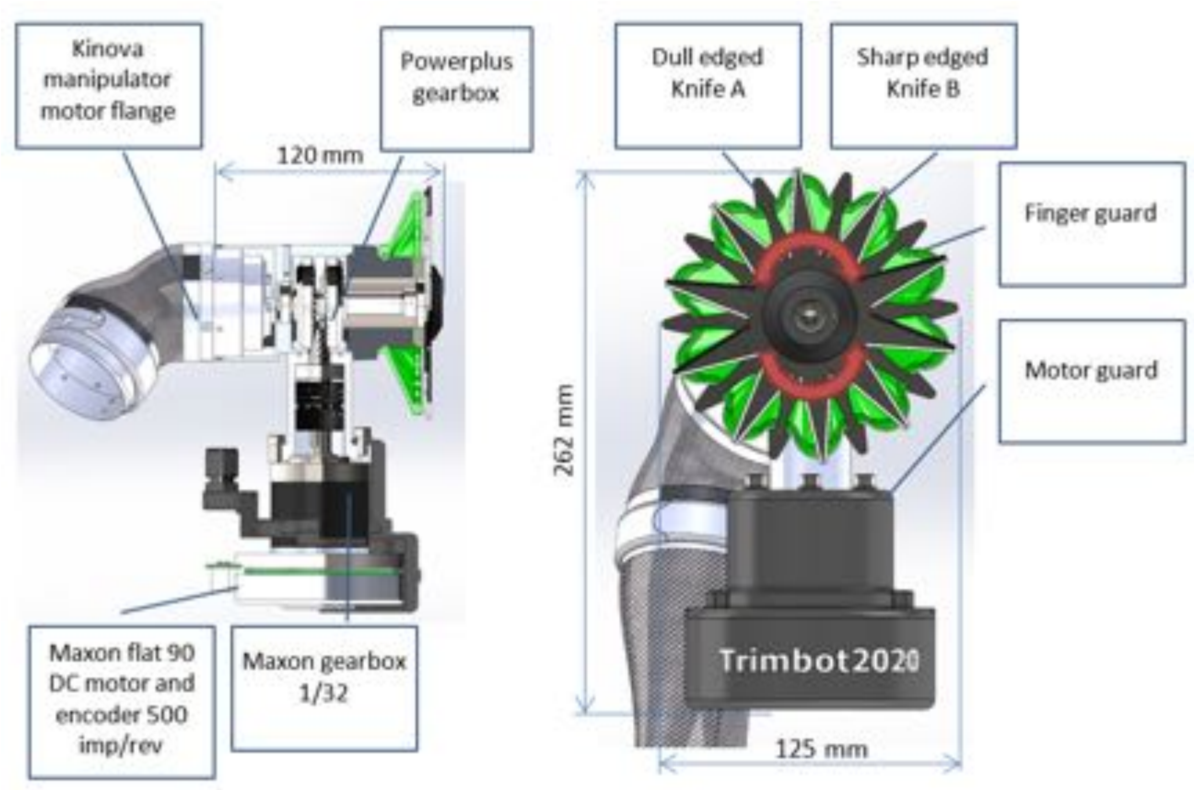

Figure 10: Cross section view (left) and front view (right) of the first prototype of the bush trimmer. Total weight is 1.8 kg.

Vineyard pruning bears similarities to rose pruning; two attempts have been made to automatically prune vineyards. The first is a French robot called Wall-Ye a second is developed by Vision Robotics Corporation http://www.visionrobotics.com/vr-grapevine-pruner, see Figure 12.

Both robot systems use scissor type end-effectors to prune individual vine branches.

2.3.2 Evaluation

In Trimbot, our aim is to prune individual rose branches from a bush. Concluding from our research electric scissor type cutters fit that task well. The first prototype will be build following the design of an electric cutter and flange mounted on the manipulator.

2.3.3 Design

After a short review of available electrical cutters, the Bosch Ciso electrical pruner was chosen to be modified so that it could be mounted on the manipulator. The main features of this device are that it can cut through 14 mm of softwood and it has a sensor build in to sense when the knife is completely open or closed. To monitor the drive system the original DC motor will be replaced by a servo controlled DC motor. During field testing we will be able to control the speed and motor current and fine tune the cutting action accordingly.

Figure 11: Manual and electric (rose) pruning tools.

Figure 12: Wall-Ye vineyard pruning robot. Picture from: http://singularityhub.com/2012/11/26/automation-reaches-french-vineyards-with-a-vine-pruning-robot/ . Wall-Ye was developed by inventors Christophe Millot, and Guy Julien. Right, Vision Robotics Corporation vineyard pruning robot. Picture from: http://www.winesandvines.com/template.cfm?section=features&content=65505.

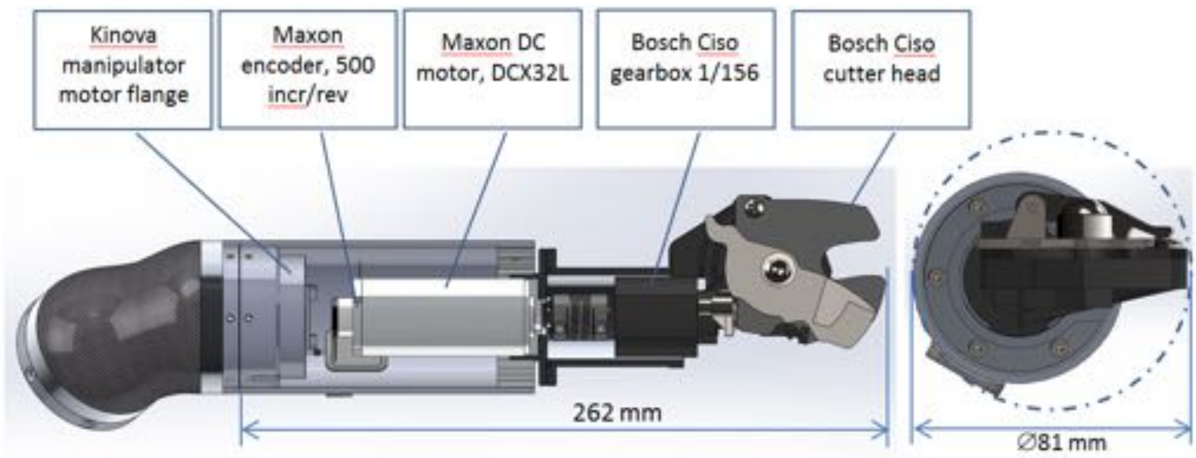

Figure 13: Cross section view (left) and front view (right) of the first prototype of the rose cutter. Total weight is 0.5 kg.

3 Arm/Platform integration

The arm and platform integration is separated in three parts: mechanical integration, electrical integration and software integration. The mechanical integration includes the mounting concept for the arm on the vehicle and is presented in Section 3.1. The electrical integration with emergency stop concept is presented in Section 3.2 and for the software integration a short devices overview is given in Section 3.3. The detailed description of the software integration concept is included in the software architecture document[1].

3.1 Mechanical Integration

The final demonstrator which has to carry the arm is based on a commercial BOSCH Indego lawn mower. For the arm and sensor integration the shell of the lawn mower is removed and an additional aluminium frame is mounted around the entire vehicle. A CAD model of the modified lawn mower with integrated arm is shown in Figure 14. For stability reasons the mounting point of the arm is in the centre of the vehicle, on the lower aluminium frame. A 40×40 mm aluminium profile fixed on aluminium plate is used as mounting adapter. A detailed view of this mounting concept is shown in Figure 15.

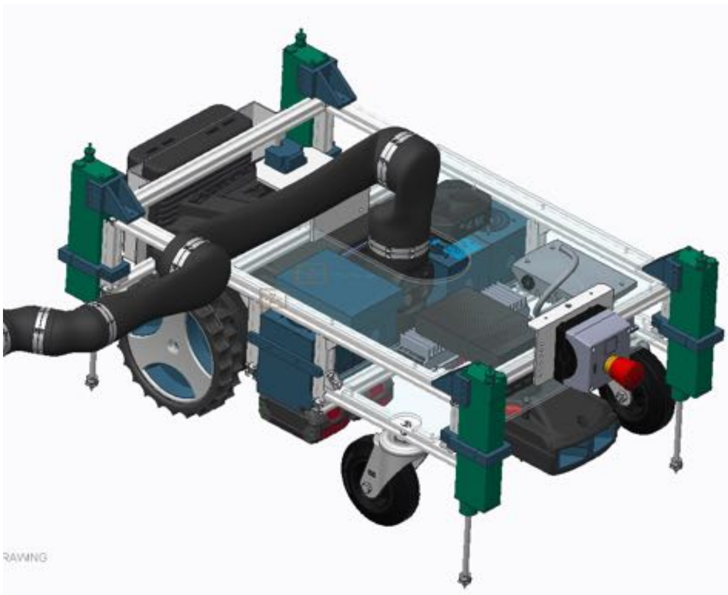

Figure 14: Overview mechanical intgration concept

3.2 Electrical Integration

The electrical integration includes the power concept for the arm and trimming tool as well as an emergency stop concept. In order to supply the arm, the trimming tools and all necessary computers with power, four additional batteries will be integrated into the vehicle. It is planned to use the lightweight BOSCH 18 volt Li-Ion compact batteries. Two of these batteries will be used for the computers and other electronic devices and two will be used for the arm, trimming

[1] https://gitlab.inf.ed.ac.uk/TrimBot2020/General/blob/master/architecture/software/software_architecture.pdf

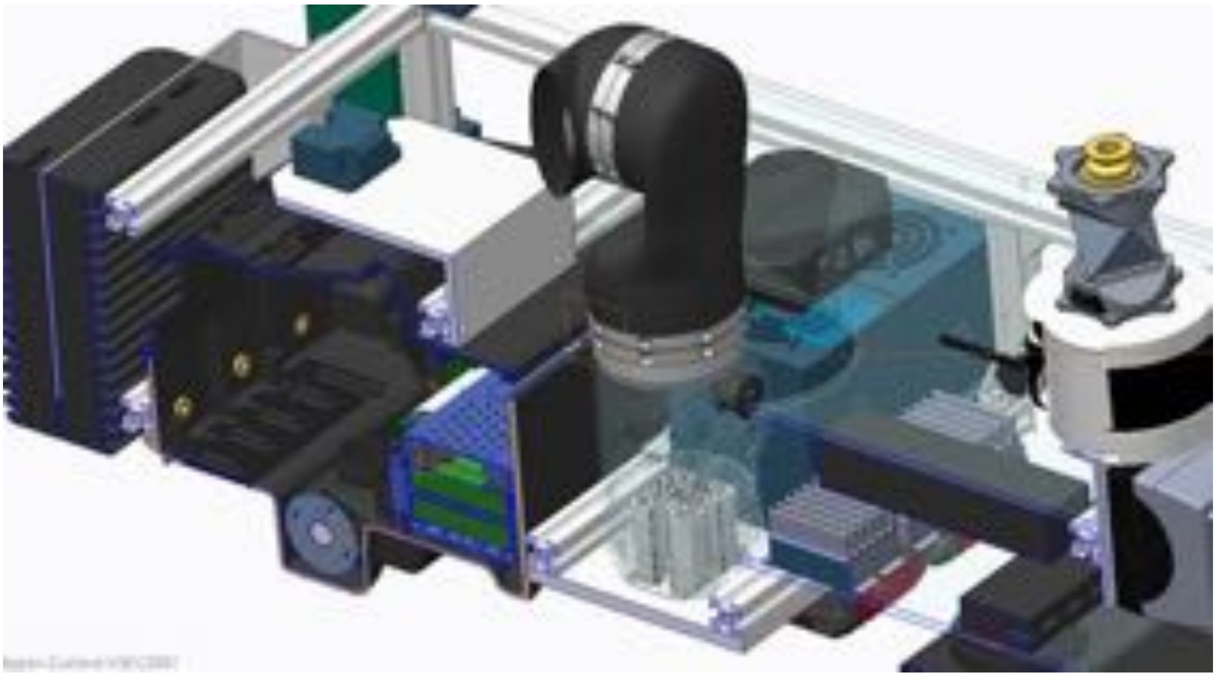

Figure 15: Mechanical integration concept with mounting plate and profile.

tool and the supporters of the vehicle. The batteries for the computers and the electronic devices are used in parallel mode with a hot swap system to change batteries during an operation without losing power supply for the computers. The batteries for the arm and trimming tool are used in series connection to reach a higher voltage level of 36 volt. An overview of the electrical concept including only the components related to the arm and trimming tool integration is shown Figure 16.

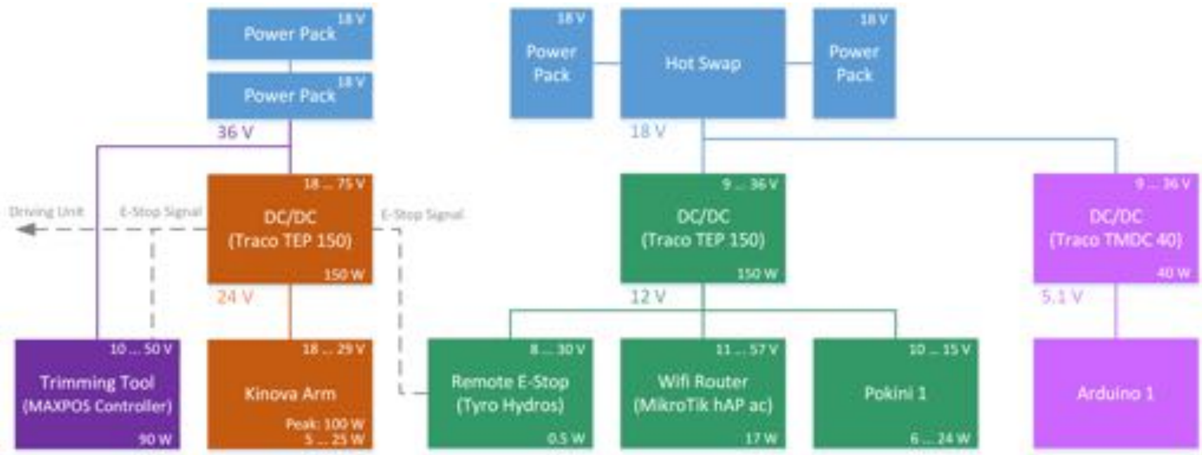

Figure 16: Electrical components related to the arm and trimming tool integration.

The power concept includes several voltage levels to support the needs of each device. The Maxon MAXPOS Controller for the trimming tool is connect to the 36 V level of the parallel battery pack. All the other devices are connected to DC/DC converters which provide the required voltage levels. The Kinova arm is connected to the 24 V level of a DC/DC converter which is connected to the parallel battery pack. The Pokini computer, the Wifi Router and the remote E-Stop receiver are connect to the 12 V level of a DC/DC converter which is connected to the hot swap system. Additionally, there will be a 5.1 V level for devices such as an Arduino or an USB hub.

The emergency stop concept is based on a certified remote E-Stop from Tyro Remotes. It is planned to use a Tyro Remotes Aquarius receiver and a Tyro Remotes Indus AQ transmitter. Both are shown in Figure 17. This system has an outdoor operating range up to 300 m. Table 5 gives some more selected specifications. More detailed information about the remote E-Stop transmitter and receiver is given in the data sheet[2]. The signals from the Aquarius receiver are connected to the MAXPOS controller of the trimming tool to enable an emergency stop of the tool and to the DC/DC converter to interrupt the power supply for the arm. These emergency stop signals can also be seen in Figure 16.

Figure 17: Tyro Remotes E-Stop transmitter and receiver.

3.3 Software Integration

The software integration is handled using the Robot Operating System (ROS). The interfaces of software components are ROS messages. A detailed description of the entire software architecture including a definition of all interfaces also for the arm and trimming tool integration is given in the software system architecture document[3].

[2] https://www.tyroremotes.de/wp-content/uploads/2015/10/Produktfolder_868_MHz_Aquarius_DE_05.pdf
[3] https://gitlab.inf.ed.ac.uk/TrimBot2020/General/blob/master/architecture/software/software_architecture.pdf

Technical Specification	
Frequency	868 MHz
Operating voltage	8-36 Vdc
Operating temperature	-40°C up to 85°C
Range (free field)	Up to 300 m
Reaction time	$<$ 100 ms
IP rating	IP68

Table 5: Specification for Tyro Remote Aquarius E-Stop receiver.

The controllers for the trimming tool and for the arm are connected via USB to the Pokini computer where the ROS software nodes are running. A remote laptop is connected via Wifi to remote control the robot, the arm and the trimming tool. An overview of this communication concept is given in Figure 18.

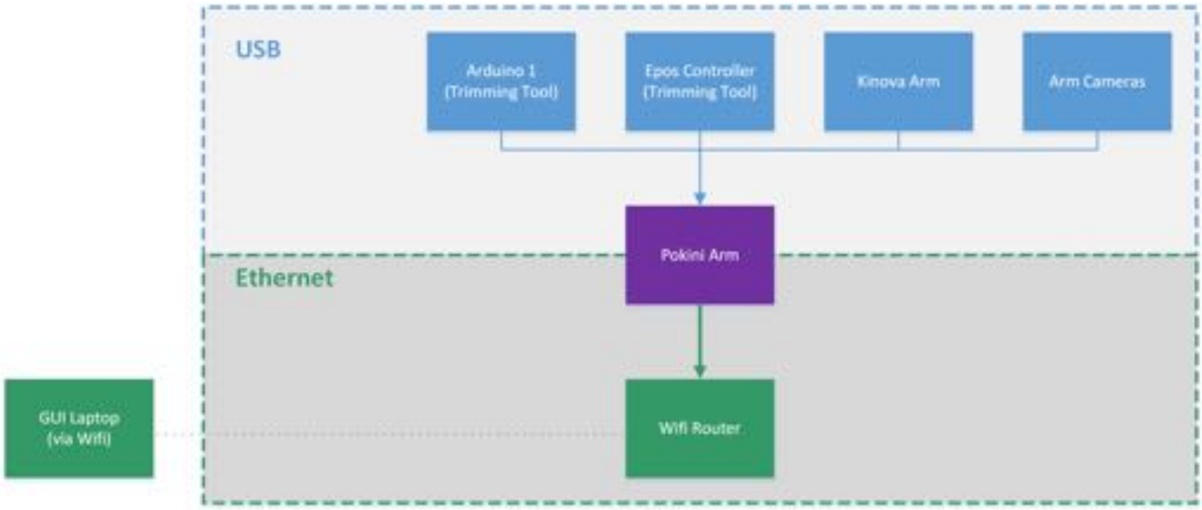

Figure 18: Communication concept for the arm and trimming tool integration.

4 Motion planning

4.1 State-of-the-art

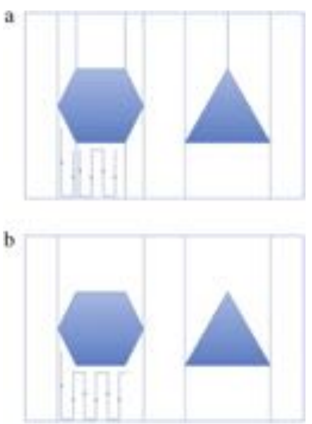

Figure 19: a) Trapezoidal decomposition b) Boustrophedon decomposition. Picture from [14].

The motion task required for automated bush trimming requires to solve a $coverage\ path\ planning\ problem$. In such kind of problem, the task space is a surface or volume that has to be fully covered in a way that avoids obstacles and minimizes some cost measure. A review of coverage path planning is provided in [14].

The task is fundamental to several robotic applications: agricultural fields plowing [17], crops harvesting [30], lawn mowing [3], inspection of underwater structures [11], environment surveillance with UAVs [24], spray-painting of automotive parts [28], spray forming [27], CNC machining [22], laser cutting [21], cleaning [25], just to name the most popular ones.

In principle, surface coverage might be performed with a randomized approach (as it is the case for some vacuum cleaning robots [25]). Randomizing the traversal order of surface patches ensures a minimal computational complexity and ease of implementation. However, such approach is inadequate for a trimming robot: having to deal with a 3D working environment, the resulting motion complexity and effort would result to be unsustainable. Moreover, uniform material removal intrinsically requires to sweep across adjacent surface patches.

Coverage path planning is intimately related to the Traveling Salesman Problem (TSP). Given a graph $G = (V, E)$, with $E \subset V \times V$, and a distance (cost) function defined for each edge in E, the aim of the TSP is finding the shortest tour of the graph visiting each node exactly once, according to the cumulative traveled distance. Since the TSP is proven to be a NP-hard problem, the computational time required to solve it drastically rises as the size of the input graph rises. Even the so-called $lawnmower\ problem$ [3], consisting in finding a path to remove all the grass in a region of grass, is proven to be PSPACE-hard, which implies NP-hard [19]. This holds even in the most basic case, where obstacles are absent.

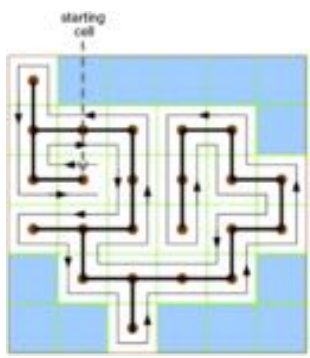

Figure 20: Grid-based coverage path using a spanning tree. Picture from [14].

4.1.1 Coverage of 2D surfaces

Classical solutions for 2D surfaces rely on simple heuristics. One popular approach consists in decomposing the free space into cells that can be covered by means of back and forth motions, as it happens with the trapezoidal decomposition [18] and the Boustrophedon decomposition [8], shown in Figure 19. By representing the environment with a graph structure based on a Boustrophedon decomposition, Mannadiar and Rekleitis [23] showed that a minimal coverage path could be found in polynomial time. Boustrophedon decomposition can handle only polygonal, planar obstacles. An extension of the technique that can deal with generic obstacles is the Morse decomposition [2].

Grid-based methods represent another popular heuristic. Such methods use a representation of the environment decomposed into a collection of uniform grid cells. Gabriely and Rimon [12] proposed an algorithm, called Spanning Tree Covering (STC), that partitions the working area into combinations of four cells, each corresponding to a square-shaped approximation of the coverage tool (Figure 20). It determines a spanning tree of the graph induced by the cells, while covering every point precisely once.

4.1.2 Coverage of 3D surfaces

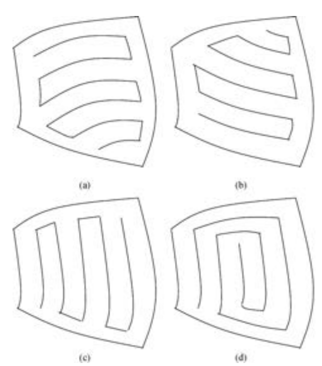

Figure 21: Candidate motion patterns for uniform coverage of automotive parts. Picture from [27].

The approaches discussed so far are only suitable for coverage of 2D environments. Atkar [4] introduced a method to generate a *seed curve* and a speed profile that guarantee paint deposition uniformity over simple automotive parts. Sheng [27] proposed a technique for automated spray forming to optimize both motion performance and material deposition uniformity. First the automotive part is segmented according to topology and normal direction, then movement patterns and optimal sweeping directions are computed. Sweeping or spiraling motion patterns (Figure 21) are utilized according to the the geometric characteristics of the part.

In the field of agricultural coverage Jin [17] developed a method to minimize headland turns and soil erosion for 3D agricultural field operations. The field is partitioned into regions sharing common features, and a seed curve based on a customized cost function is computed for each region. Bochkarev [5] proposed an alternative method for robot turns minimization based on approximate convex decompositions. Hameed [15] developed an algorithm able to determine the optimal driving angle and the corresponding sequence of swaths over 3D agricultural fields. Recently Dogru [10] solved the coverage path planning problem in terms of energy consumption. He used a genetic algorithm and took into account the constraints of natural terrains: obstacles and relief.

These applications do not involve contact between the tool and the surface. Moreover, they focus on partitioning the object into easy-to-handle regions, more than on generating trajectories that are convenient for the mechanism.

4.1.3 Coverage in the robot configuration space

The previous works are based on extending the simple control policies of 2D coverage planning (based on the repetition of a sweeping pattern) over 3D structures and environments. When implementing coverage path planning with a manipulator arm, the motion planning module needs to deal with the specific capabilities and limits of its kinematic structure. For a bush trimming robot this is especially relevant, since the robot arm has to deal with a large 3D surface spanning a remarkable portion of its workspace. Thus, planning the tool path in the Cartesian space would lead to dishomogeneity in the joint torques required to sweep different cutting areas. The cutting motion would turn out to be irregular and energy-wasting. Thus, coverage paths should be computed in the *configuration space* of the robot. [26] [11]

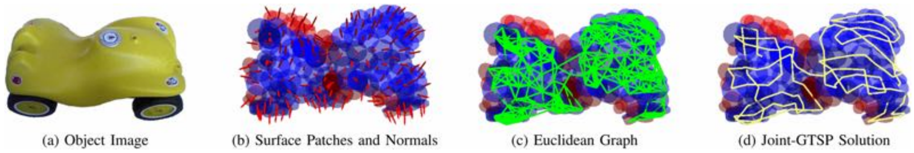

Figure 22: Extraction of a set of planar patches describing a 3D object and computation of the shortest coverage path according to an objective function defined in the robot configuration space. Picture from [16]

Hess [16] implemented a framework for 3D surface coverage by a redundant manipulator. Multiple kinematic solutions are represented as individual nodes in a graph and the problem became finding a graph tour minimizing a user-defined function in the joint configuration space, as shown in Figure 22. Although this work represents a relevant paradigm shift in the field of coverage path planning, it does not take into account the effects of the actual physical interaction between the tool and the surface. More recently, Leidner [20] presented a method to perform wiping tasks with a redundant robotic agent. This work is based on a semantic representation of different kinds of cleaning actions for household chores. The medium of the wiping task is described by a particle distribution, while the motion plan to clean the surface is generated as a graph search problem, where each edge is an interpolated tool motion in contact with the surface.

In these last two works, optimization of the joint motions is achieved only through exploitation of redundant joints. Furthermore, there is no guarantee that the originated trajectory has a jerk-bounded profile. This is critical for a trimming task, since non-smooth movements would entail further mechanical stresses and vibrations to the ones induced by the plant cutter itself.

4.2 Innovation

In contrast to classical coverage *path* planning algorithms, the to be developed algorithm will implement coverage *trajectory* planning, that is, the focus will not be just on *where* the robot moves, but also on *how* it moves. Our main contributions will be:

- the development of a general framework solving the automatic bush trimming problem, given an arbitrary serial robot kinematic structure and arbitrary bush shapes;

- the implementation of a new coverage motion planning pipeline that generates optimal trajectories in terms of manipulation effort, completion time and motion smoothness (to the best of our knowledge, no existing work on coverage path planning for manipulators considers all the three aspects simultaneously);

- an experimental analysis of how the generation of such optimal trimming trajectories impacts the aesthetic properties of the final bush surface resulting from the trimming task.

4.3 System design

A motion planning algorithm for robotic bush trimming is expected to generate a reference trajectory of a robot arm endowed with a plant cutter. This task requires as input the 3D models of 1) the robot arm, 2) the plant cutter, 3) the target bush boundary. In principle, we would require also the model of the initial bush boundary. Anyway, if we assume a thin layer of superfluous leafy material, it is possible for the plant cutter to erase the overgrown portion of the bush while constantly being in contact with the target boundary. Two classes of performance indicators will be evaluated: the robot performance indicators (manipulation effort, completion time, motion smoothness) and the trimming performance indicators (cutting error, bush boundary smoothness). An overview of the framework is shown in Figure 23.

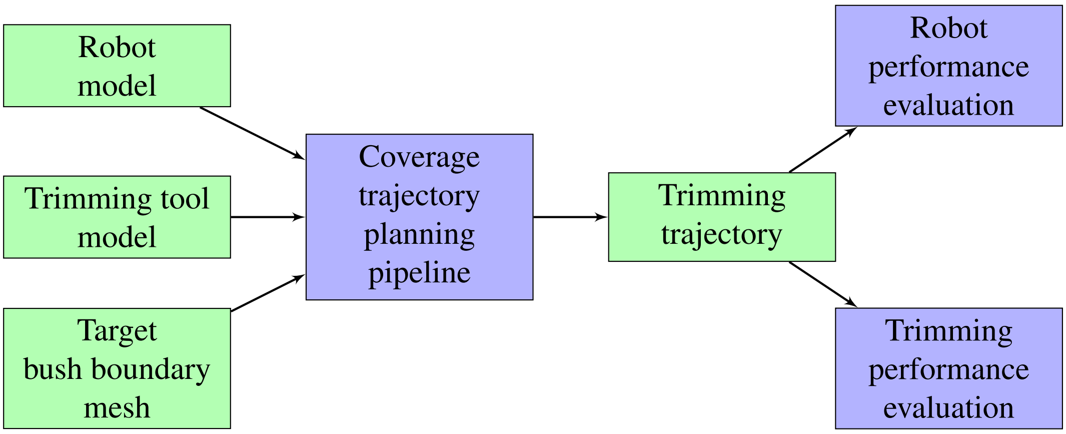

Figure 23: Bush trimming framework overview.

The trimming trajectory planning pipeline is divided into three submodules: 1) the planning setup module, 2) the coverage planning module, 3) the trajectory planning module. The planning setup module processes the inputs to generate the search space for the actual planning task. The coverage module produces a list of intermediate joint configurations to be traversed to achieve coverage of the cutting area with the tool. The trajectory module interpolates the intermediate joint configurations into a smooth temporal motion law. An overview of the trimming trajectory pipeline is shown in Figure 24.

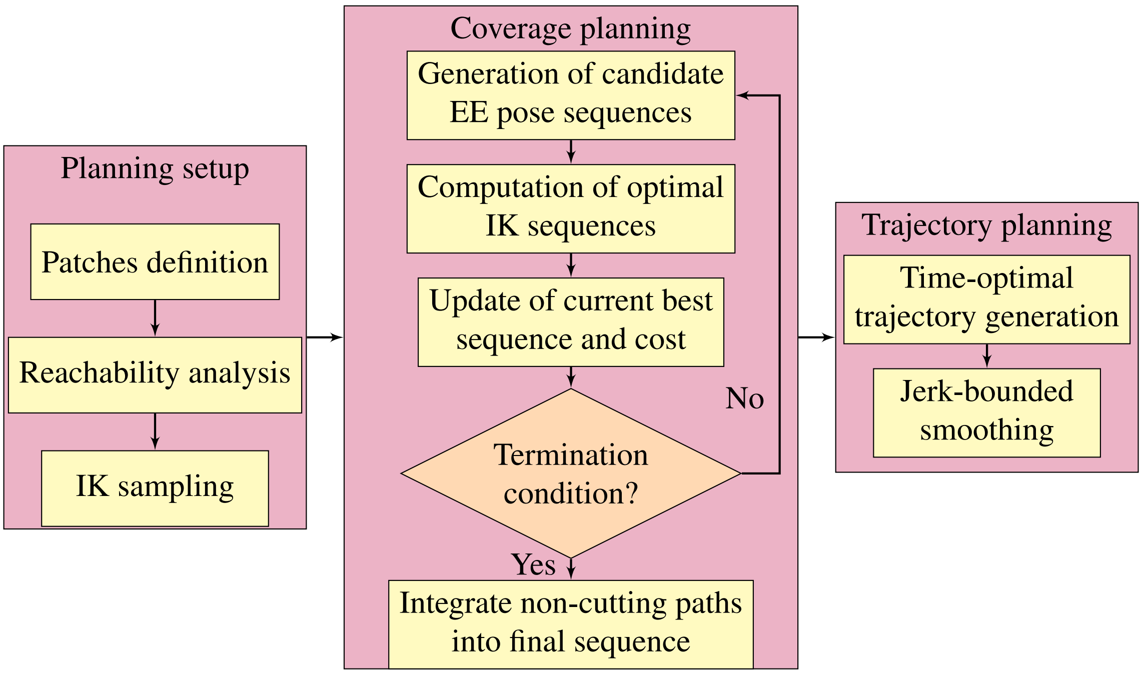

Figure 24: Coverage trajectory planning pipeline (EE=end-effector, IK=inverse kinematics).

5 Vision-based replanning

The previous section investigated the design of a sense-plan-act approach for motion planning for bush trimming. In a real-world scenario, a perfect prior knowledge of the working environment of a bush trimming robot is unrealistic due to different kinds of dynamical modifications arising in the real world: imperfect surface reconstruction, non-static surface of plants, humans walking in the area. In the following, the possibility to extend the framework with real-time replanning capabilities is discussed.

5.1 State-of-the-art

5.1.1 Coverage planning accounting for environment uncertainty

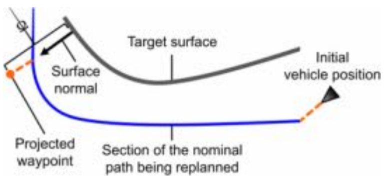

Figure 25: Trajectory construction in a replanning step presented in [13]. The path consists of both the slice of the nominal path (blue) and the added segments (orange).

One of the earliest works about the sensor-based coverage problem is the one by Acar and Choset [1] [2]. They introduced a method to detect in real-time the critical points of a Morse-based boustrophedon decomposition by exploiting a range sensor, by detecting the critical points of the obstacles along the way. This work limits to perform on-line update of the environment description, while keeping the traditional back-and-forth coverage strategy. Xu [31] exploited several graph search algorithms to plan the coverage of environments that can be represented as graphs, such as road networks. He implemented partial coverage with replanning capabilities for a single robot and for a team of robots, by modeling the problem as a Rural Postman Problem. These works consider topology change in the environment, but not uncertain positioning of the robot.

5.1.2 Coverage planning accounting for robot uncertainty

Bretl and Hutchinson [6] were able to guarantee complete coverage of a planar workspace under uncertainty in control, by assuming a worst-case bound for the positioning and velocity error. More recently, Galceran [13] implemented a coverage planning algorithm for underwater structures. He presented an replanning algorithm based on stochastic trajectory optimization, to adapt a coverage path based on an initial bathymetric map in real-time using range sensor measurements. An example of replanning step is shown in Figure 25. These works account for uncertain positioning of the robot, but not with dynamical modifications of the description of the target structure.

5.1.3 Coverage planning accounting for robot and environment uncertainty

A bush trimming robot needs to deal with both dynamical modifications of the description of the target environment and with uncertainty about the robot positioning with respect to that environment. Even if the control system of the manipulator is highly reliable, the acquired description of the bush at the beginning of the planning task might induce it to generate an incorrect motion plan. When the robots gets close to the bush surface, it might update the local surface description according to a wrong assumption about where it is currently located within the *map* of the bush. Thus, we need to estimate in real-time the target surface as well as estimate in real-time the positioning of the robot with respect to the target surface.

Chaves [7] proposed a path planning algorithm integrated with SLAM to find revisit paths for a robot exploring an uncertain environment. Vallvé [29] studied how to simultaneously decrease map and path uncertainty through exploratory trajectories defined in the robot configuration space. Davis [9] solved the problem of planning a path from a start state to a goal state while maximizing the coverage of a target region and minimizing the the probability of collision with the environment (Figure 26). He introduced c-OPT, an algorithm that optimizes trajectories in the belief space. Although this work is related to our proposed approach, it is only based on finding locally optimal paths and does not exploit any plan based on a global model of the scene. No-one of these works considers a robot physically interacting with the surface to be covered and modifying its state, and no one of them performs coverage with a manipulator.

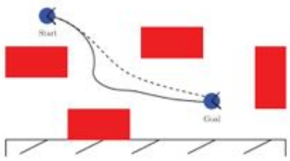

Figure 26: Point-to-point optimization with C-OPT. The dashed line is a collision-free trajectory, the solid line maximizes the views of the target wall. Picture from [9].

5.2 Innovation

The new module will implement a trajectory-reshaping system based on accurate local information about the target surface. The robot will compute an initial trimming trajectory according to the acquired global surface model. Then iteratively it will examine the bush portion currently within the field of view of the camera, in order to localize itself with respect to the bush and adapt the local trimming trajectory slice.

Our main contributions will be:

- Design of a vision-based, closed-loop motion planning algorithm for bush trimming;
- Design of a comprehensive framework for robot localization, bush surface mapping and motion planning (no active SLAM-based architecture currently exists in the field of coverage with a robot arm);
- Implementation of a new trajectory reshaping system based on real-time local optimization over a global path, by exploiting local surface close-ups.

5.3 System design

The vision-based replanning system will be built on top of the open-loop trimming planning module. The open-loop pipeline will generate a preliminary plan. Then there will be two new modules: 1) a filtering module, in charge of estimating the robot location with respect to the bush as well as the local target cutting area, and 2) a trajectory reshaping module, that takes as input the base plan, the current estimations of robot state and surface slice, and produces a locally optimal trimming trajectory segment. An overview of the system is shown in Figure 27.

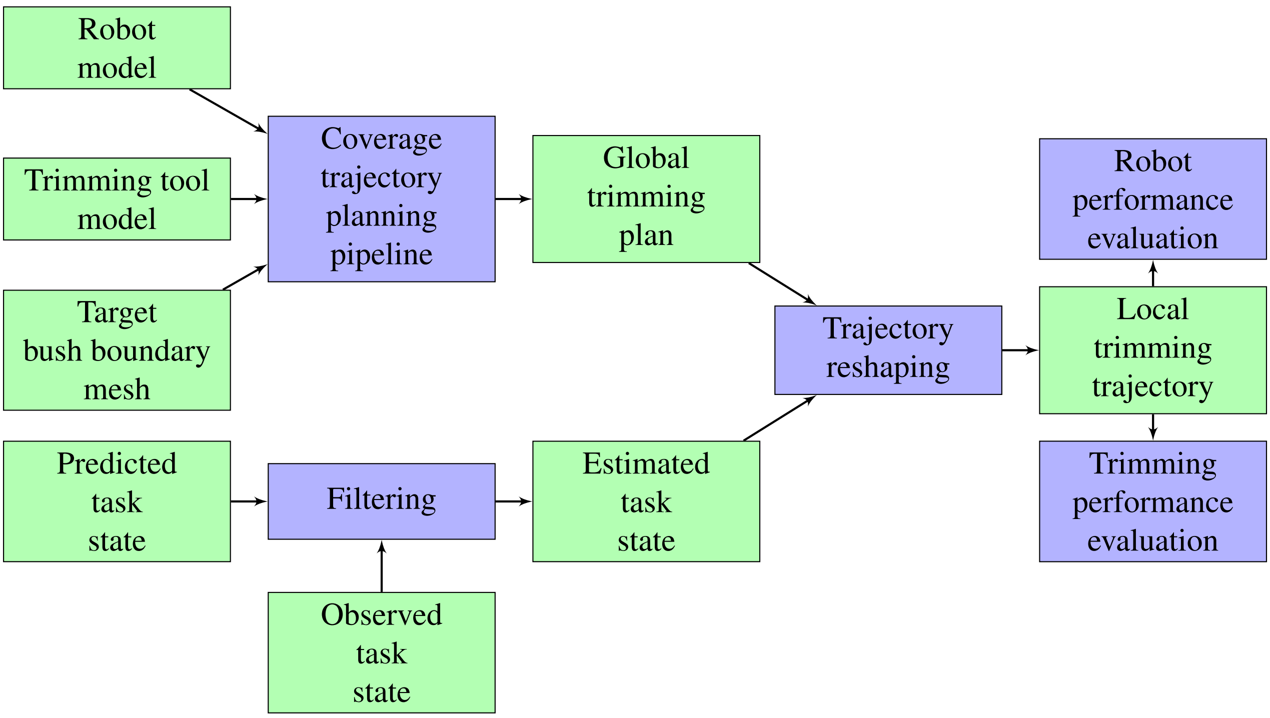

Figure 27: Bush trimming with replanning framework overview.

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