Eden Robotics Report

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Introduction

Project

This project was realized as part of our studies in connection with the company "ALL one Robotics". The initial objective was to build a robot to pick apples. Our client had noticed a great shortage of manpower in French and American farms. In France alone, 1 million seasonal workers are needed for the harvest. This labor force remains difficult to find and the crisis of the cider has amplified this phenomenon. Thus, in the United States only 807. of the apples would be picked, resulting in significant economic and food losses. This problem has given the idea to our customer to remotely operate the harvest, giving birth to the project "All One Robotics".

It is a project of 18 months of 12 students of the Ecole Centrale de Lille whose objective is to build a robot capable of picking apples and content remotely With the means available and the difficulties encountered, the project turned to the rind of tomatoes We had to build a prototype and this would facilitate and accelerate the work.

Our Client, Patrick Kedziora is a French-American entrepreneur and founder of the start-up "All One Robotics". We could also count on coaches from Centrale Lille who helped us throughout the project, especially for the management of such a project: Mr. Denis le Picart and Mr. Roland Marcoin.

Team members

In this project we were 12 students in the first year of the Ecole Centrale de Lille : Anna Berger, Anna Ducros, Antoine Alessandrini, Aya Skhoun, David Kirov, Héloïse Boyer-Vidal, Maxime Baquet, Noé Luxembourger, Simon Dahy, Simon Kurney, Thomas Jaouën et Victor Guinebertière. 11 of us came from preparatory classes (from all section) and Simon K. was in double degree with his university in Germany.

1 Project definition

1.1 Market study

At the request of Mr. Kedziora, we began by conducting a market study. Even if he had already done it, it allowed us to better understand the expectations of our customer, the possible difficulties but especially to have the point of future users of our product.

Mr. Kedziora's will being to market the robot in the United States, we focused on this region even if we also studied the situation in France. For that we contacted farmers by asking them questions about :

- The size of their farms
- The method of collection and the duration
- The points of attention to pick apples
- The type of soil
- The difficulties encountered in finding personnel
- The interest for the use of robot : motivation and fear.
- The possible price.

It turned out that only the big farms (¿ 50 acres) were interested. Indeed, out of the twenty or so farms that we contacted, more than 80% were having difficulty recruiting, especially with the Covid crisis. This is not the case for small farms because they work mainly with local people and need fewer people. Thus, all the large farms were in favor of using robots. However, they warned us about the current existence of autonomous robots and the need to distinguish themselves. According to them, the big disadvantages of robotization today are: the price of access and maintenance. A remote-controlled robot can answer their request by reducing the cost. However, our robot must keep the advantages of autonomous robots: work all day, less personnel present. The continuous work is a primordial point because the robots are generally slower than the humans but can thus a better output on a complete day. Finally, technical characteristics were also put forward: Not too much pressure on the fruit, ability to drive on potentially muddy dirt roads, dimensions to respect.

We also went directly on the spot to visit orchards in order to have a better vision of all these constraints and to be able to better discuss with the farmers. It was thus of a great help to write the specifications.

1.1.1 State of the art

1.1.2 Arm

1.1.3 Base

1.1.4 Sensors

1.1.5 Communication

1.1.6 Storage

1.2 Definition

After conducting a market study and a state of the art, we were able to redefine the project. Initially, our client wanted us to design and manufacture a complete robot: a base and an arm. His main constraint was the flexibility of the robot to be able to adapt to other tasks and thus be used throughout the year. As we have seen in the state of the art, many bases already exist and are relatively cheap. Moreover, Mr. Kedziora also wanted us to start from a blank page in

order not to be influenced by the existing, so it would have taken too much time to focus on everything. So, with his agreement, we decided to focus on the arm, the hand and the control system.

Indeed, the main point of this project was to recover the fruits without damaging them. The hand was therefore the central element to distinguish us. We also kept the creation of the arm because the robot had to have a low cost and we wanted to imagine the least expensive design. For the same reason, we also kept the implementation of the control system.

Finally, during the course of the project and facing the difficulties we encountered, we also evolved the project during the year. The apple harvest became the cherry tomato harvest. This allowed us to reduce the dimensions of our robot while keeping almost all the constraints to respect. We were therefore able to make all the prototypes with the "traditional" tools of the plant. We were also able to meet the flexibility criteria required by our customer.

1.3 Specifications

Following this, we made a specification. These studies as well as the evolution of the project allowed us to estimate the expectations and constraints.

The general cases of use that we could list are the following :

- Picking up
- Storage of fruits
- Storage of robots
- Cleaning of the robot
- Recycling (not treated in the following)

We then made an "octopus diagram" which illustrates the links between the different functions:
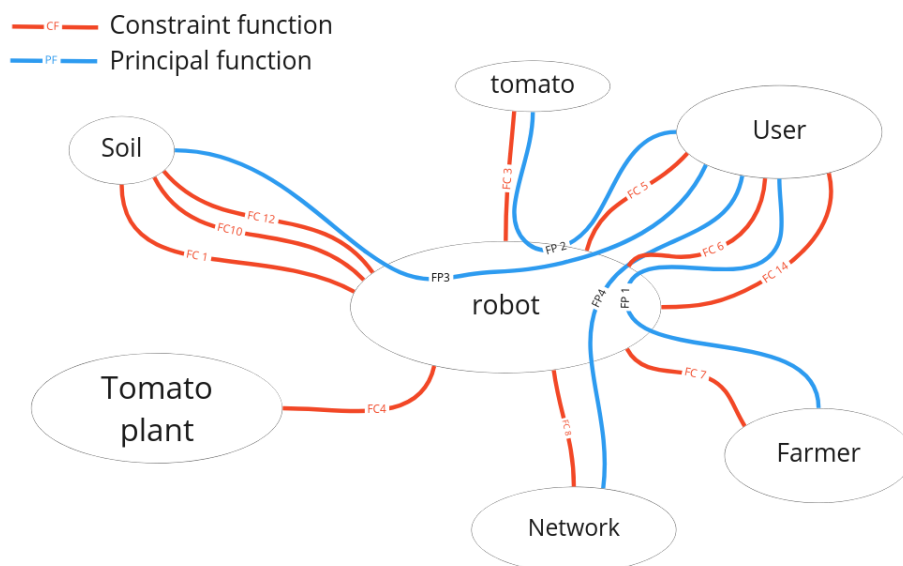

Figure 1: Octopus diagram

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Only the main functions are presented here, the entire specification can be retained in appendix A. The main function is to be as efficient as a humour over a day. Thus the arm will have to retrieve a tomato in less than 10s.

Principal Function	Appreciation criteria	Level	flexibility
PF 1: Be at least as efficient as a human	harvest duration	less than 10s	F2
PF 2: Picking tomatoes	The tomatoes are detached	80% of standard orchards are collect	F1
PF 3: Controlling the robot	Pick tomatoes	get 80% of tomatoes	F2
PF 4 Control the robot remotely	User can be in other place	500m distance	F2

The main constraint function is to reach all the tomatoes. To measure this, we want our robot to be able to reach 80% of the tomatoes in a standard orchard.

Constraint Function	Appreciation criteria	Level	flexibility
CF 1: Keeping tomatoes intact	Forces exerted	less than 5N	F1
CF 2: Avoid branches and tomatoes	Precision	relative gap¡1cm	F1
CF 3: Be easy to pilot	User feeling	Learn time¡2h	F2

2 Project Management

2.1 Organization

2.1.1 Non technical aspect

To manage the project in the best possible way, we defined from the beginning the non-technical roles to be taken in charge. The objective was to avoid the "tunnel effect" on these tasks which can be considered as secondary. They are however essential for the success of such a project.

We appointed a project manager in charge of transmitting information to all members and especially to the different technical poles. His mission was to ensure a follow-up of the progress as well as the update of the communication tools.

In order to help him, we also put in place a person in charge of the external communication. He communicated with the coaches as well as with the external stakeholders. Like the project manager, he was also in permanent communication with the client. In order to manage the budget as well as possible, financial provided for the client but also the possible trainings. Budget and training managers were appointed.

Charges		Person in charge
Transmission of information between the poles		Project manager
Project management tools		Antoine, Maxime, Anna B, David
Budget		Héloïse
external coordination		Victor
Training management		Anna B
Write Meeting report		Everybody

Figure 2: Non Technial organization

2.1.2 Technical aspect

After having defined the project we were also able to define a technical organization. Three poles were created.

First a mechanical pole whose role was to design the different versions of the robot. Then to build it. An automatic pole in charge of the simulation of the robot and the control system. Finally a IT pole They worked on the user interface, the video acquisition and the remote connection.

Each pole had a person in charge to facilitate the follow-up. These regularly discussed with the project leader.

Figure 3: Technial organization

2.2 Planification

In order to manage the progress of the project, project management tools were put in place. They were updated at least weekly.

First of all a WBS (Work breakdown structure) was created. Its purpose is to break down the project into smaller pieces. It allows us to identify more precisely all the work to be done and the distribution between the different poles.
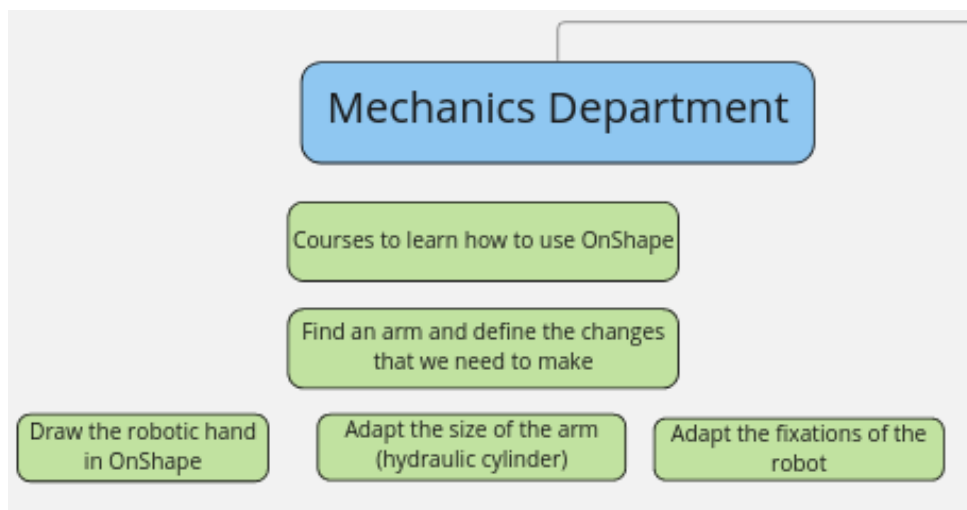
Figure 4: WBS exemple

Thanks to this document, we set up a Gantt chart. It illustrates the project schedule by indicating the tasks to be accomplished and the time. Each pole had its Gantt chart, which were linked to a global chart. This allowed us to anticipate certain delays and adapt. Milestones were also defined in order to have objectives all along the project. Their date were set on the audits during the project.

Figure 5: Gantt exemple

Finally, to manage the daily tasks and ensure both a good distribution of work between members and their achievement we used a to- do-list. It indicated the tasks to be carried out, the person in charge, the person in charge who followed the progress, the date and the status.

Figure 6: To do list exemple

2.3   communication

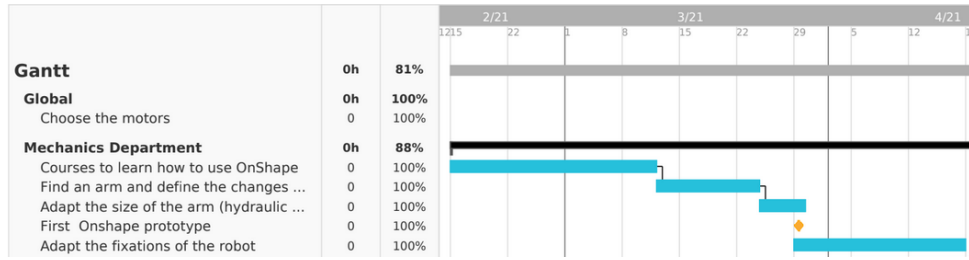Communication was a key point for success. We were fortunate to have a client who was very involved in the project. Thus, we had weekly meetings with him to review the progress. It was also an opportunity to take advantage of his expertise on the management of such a project as well as his ideas. During these meetings we discussed both the technical and management aspects. He also allowed us to meet people such as the CTO of BMW who gave us precious advice. At the request of Mr. Kedziora, we did not have a person in charge of taking notes. A schedule was defined in order to have a rotation between all the members and all benefit from this experience. A template for the uniformity was set up.

Each pole also met one afternoon per week to work and exchange on the technical part of the project, and a monthly meeting was held between the pole managers and the project manager to ensure the smooth running of the project.

To exchange information, we had a Google Drive to store all the documents. Github folders were also created for the IT part. Finally, we also communicated with our client via Whatsapp. We also had a messenger group with all members.

2.4   Resource management

Two types of means can be taken into account. First, the direct financial expenses. These are all the purchases we made. As explained earlier, Heloise was responsible for this tracking. She could therefore easily ensure that the expenses were in line with the client's wishes. These expenses also included the use and purchase of materials from central offices.

Many non-direct expenses were also taken into account. First the cost of our labor summarized in the table below. But also the consulting hours. Indeed, Centrale offered the possibility to contact professors and to benefit from their knowledge. So we contacted different people who redirected us to the teachers who could help us the most. To ensure full and balanced use as needed, Anna kept a document describing their use.

dernière mise à jour :	Type d'achat	Lieu d'achat	Pole		Cout (€)
08/12/2020	Inscription Conférénce Fira	Site Fira	robotique	▼	39€
13/03/2021	AZ delevery cablede remplacement	Amazon	informatique	▼	4,99€
	Inno Maker Rasberry Pi	Amazon	informatique	▼	13,99€
	LEICKE 72 Alimentation	Amazon	informatique	▼	19,99

Figure 7: Financial budget extract

Matériel école	nom	prix	quantité	Temp d'impression
impression main et doigts	ASA PRO	16,28	50	5h50
impression main V2	ABS	18,8	110	18h
	ASA PRO	28,97	161	

Figure 8: Material budget extract

These hours were a great help. We were able to count on our coaches to help us manage this project. We were able to count on consultants, including Mr. Kruszewski, who were really involved in the project. Thanks to him, we were able to benefit from an almost weekly follow-up to perpetually advance the project. It was also a question of privileged moments to deepen certain subjects with them.

Pole	Number of days per person	Detail	Daily rate	Total
Mecanic	81	5 people available at 75% 1 day a week for 18 months	36,23 €	14 671,13 €
IT	81	4 people available at 75% 1 day a week for 18 months	36,23 €	11 736,90 €
Automation	81	3 people available at 75% 1 day a week for 18 months	36,23 €	8 802,68 €
			Total	35 211 €

Figure 9: Human budget extract

3 Design

3.1 Brainstorming

3.2 V1

3.3 V1

3.3.1 Arm

3.3.2 Hand

3.4 VF

4 Simulation

In parallel to the design, we simulated the operation of the robot using Matlab, Simulink and python. The work explained from now on is done on the last prototype presented in the previous section. However, the principle applied has been the same throughout the project. The simultaneous work was important in order to anticipate the delays due to the manufacturing of the robot.

4.1 Robot kinematics

Definition : Given a vector $x = [x_1 x_2 x_3]^T \in \mathbb{R}^3$, we define :

$$[x] = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}$$

Definition : Given two vectors x and y in $\mathbb{R}^3$, we define : $x \times y = [x] \cdot y$

Definition : For a joint, we define the pitch $h = \frac{v}{w}$ with v : the linear speed and w the angular speed

Definition : The screw is a 6×1 vector that represent the angular velocity when $\dot{\theta} = 1$ and the linear velocity of the origin when $\dot{\theta} = 1$. $S = \begin{bmatrix} s_w \\ s_v \end{bmatrix}$ with $s_v = hw - s_w \times q$ where h is the pitch and q is a point on the

Definition : For a given reference frame, a screw axis S is written as

$$S = \begin{bmatrix} s_w \\ s_v \end{bmatrix}$$

where either (i) $\|s_w\| = 1$ or (ii) $\|s_w\| = 0$ and $\|s_v\| = 1$. If the pitch is finite ($h = 0$ for a pure rotation), then $s_v = hs_w - s_w \times q$ where q is a point on the axis of the screw

The figure below shows the kinematics schema of the robot. The figure defines an {s} frame at the bottom, an {e} frame at the end effector position and a {c} frame at the camera position. The robot is at is home configuration. The joint are represented with the rotation (positive rotation about the axes is by the right hand rule).

The parameters can be found with Onshape and are listed below:

$L_0 = 0.069m$	$d_0 = 0m$	$h_0 = 0.06m$
$L_1 = 0.116m$	$d_1 = 0.018m$	
$L_2 = 0.16m$	$d_2 = 0.042m$	
$L_3 = 0.155m$	$d_3 = 0.01413m$	
$L_c = 0.053m$	$d_c = 0.0105m$	$h_c = 0.0815m$
$L_e = 0.2377m$	$d_e = 0.0105$	$h_e = 5.10^{-5}m$
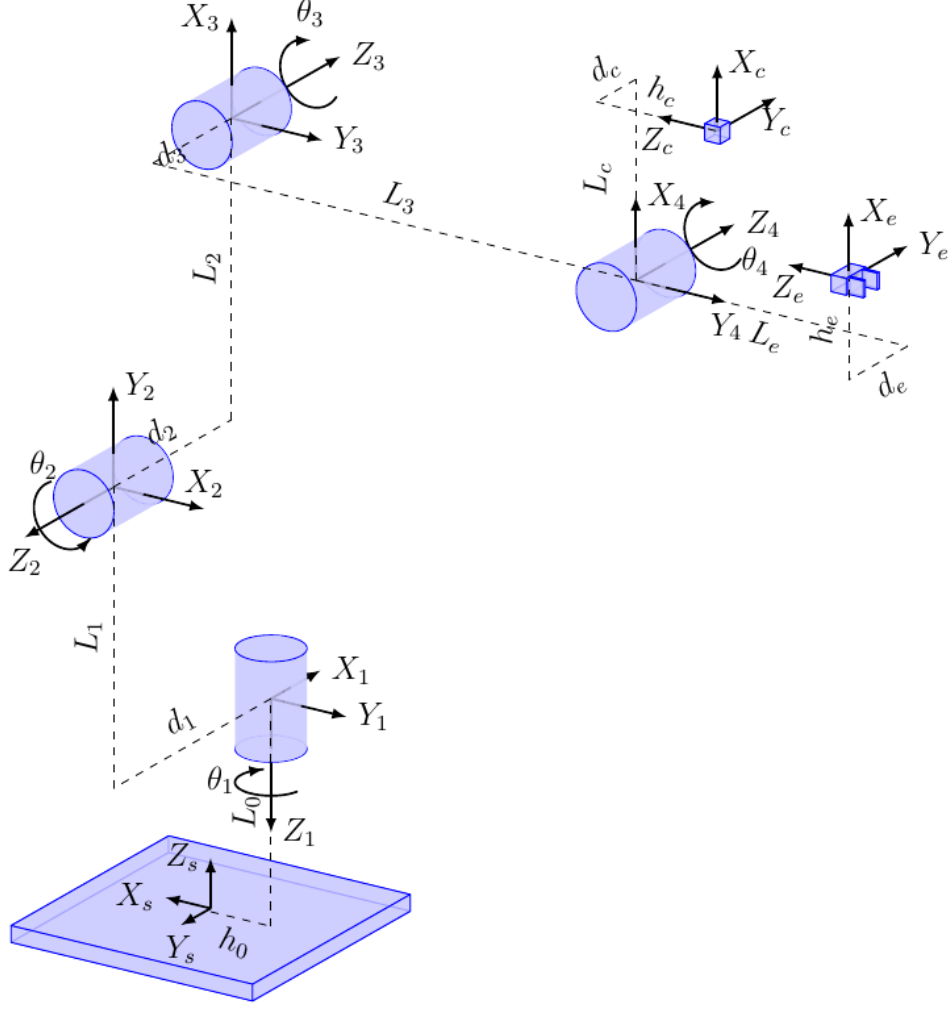
Figure 10: Kinematics schema

We can then define M_c and the M_e the transformation matrix (T_{sc} and T_{se}) when the robot is at its home configuration.

$$M_c = \begin{bmatrix} 0 & 0 & 1 & -h_0 - L_3 - h_c \\ 0 & -1 & 0 & d_1 - d_2 + d_3 + d_c \\ 1 & 0 & 0 & l_0 + l_1 + l_2 + l_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } M_e = \begin{bmatrix} 0 & 0 & 1 & -h_0 - L_3 - h_c \\ 0 & -1 & 0 & d_1 - d_2 + d_3 + d_c \\ 1 & 0 & 0 & l_0 + l_1 + l_2 + l_c \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.1.1 Base frame

In this subsection we study the kinematics parameters in the base frame {s}. It will be the one used in the followings sections.

The rotation axis S_{w_i} of each joint in {s} are :

$$S_{w_1} = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}, S_{w_2} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, S_{w_3} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}, S_{w_4} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix},$$

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We can also write the position of each joint $q_1, q_2, q_3, q_4, q_c, q_e$ in {s}. Lining up the position as columns, we get :

$$
\begin{bmatrix}
-h_0 & -h_0 & -h_0 & -h_0 - L_3 & -h_0 - L_3 - h_c & -h_0 - L_3 - L_e \\
0 & d_1 & d_1 - d_2 & d_1 - d_2 + d_3 & d_1 - d_2 + d_3 + d_c & d_1 - d_2 + d_3 + d_e \\
L_0 & L_0 + L_1 & L_0 + L_1 + L_2 & L_0 + L_1 + L_2 & L_0 + L_1 + L_2 + L_c & L_0 + L_1 + L_2 + h_e
\end{bmatrix}
$$

There are all pure rotation joint, using the position, the rotation axis and the formula define in above we can calculate the screw axis S_1, S_2, S_3, S_4 in {s}.. Lining up them as columns, we get :

$$
S_{list} =
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & -1 & -1 \\
-1 & 0 & 0 & 0 \\
0 & -L_0 - L_1 & L_0 + L_1 + L_2 & L_0 + L_1 + L_2 \\
-h_0 & 0 & 0 & 0 \\
0 & -h_0 & h_0 & h_0 + L_3
\end{bmatrix}
$$

4.1.2   End effector frame

In this subsection we study the kinematics parameters in the end effector frame {e}. However, it is not the one that will be use later.

The rotation axis S_{w_i} of each joint in {e} are :

$$
S_{w_1} = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}, \
S_{w_2} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}, \
S_{w_3} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \
S_{w_4} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix},
$$

We can also write the position of each joint $q_1, q_2, q_3, q_4, q_c, q_e$ in {e}. Lining up the position as columns, we get :

$$
\begin{bmatrix}
-h_e - L_2 - L_1 & -h_e - L_2 & -h_e & -h_e & -h_e + L_c & 0 \\
d_e + d_3 - d_2 + d_1 & d_e + d_3 - d_2 & d_e + d_3 & d_e & d_e - d_c & 0 \\
L_e + L_3 & L_e + L_3 & L_e + L_3 & L_e & L_e - h_c & 0
\end{bmatrix}
$$

There are all pure rotation joint, using the position, the rotation axis and the formula define in above we can calculate the screw axis B_1, B_2, B_3, B_4 in {e}.. Lining up them as columns, we get :

$$
B_{list} =
\begin{bmatrix}
-1 & 0 & 0 & 0 \\
0 & -1 & 1 & 1 \\
-1 & 0 & 0 & 0 \\
0 & L_e + L_3 & -L_e - L_3 & -L_e \\
-L_e - L_3 & 0 & 0 & 0 \\
d_e + d_3 - d_2 + d_1 & h_e + L_2 & -h_e & -h_e
\end{bmatrix}
$$

4.2   URDF Format

The Universal Robot Description Format (URDF) is an XML (eXtensible Markup Language) file format used by the Robot Operating System (ROS) to describe the kinematics, inertial properties, and link geometry of robots. A URDF file describes the joints and links of a robot:

- **Joints :** Joints connect two links: a parent link and a child link. A few of the possible joint types include prismatic, revolute (including joint limits), continuous (revolute without joint limits), and fixed (a virtual joint that does not permit any motion). Each joint has an origin frame that defines the position and orientation of the child link frame relative to the parent link frame when the joint variable is zero. The origin is on the joint's axis. Each joint has an axis 3-vector, a unit vector expressed in the child link's frame, in the direction of positive rotation for a revolute joint or positive translation for a prismatic joint.

- **Links :** While the joints fully describe the kinematics of a robot, the links define its mass properties. These start to be needed in Chapter 8, when we begin to study the dynamics of robots. The elements of a link include its mass; an origin frame that defines the position and orientation of a frame at the link's center of mass relative to the link's joint frame described above; and an inertia matrix, relative to the link's center of mass frame, specified by the six elements on or above the diagonal. (Since the inertia matrix is symmetric, it is onlynecessary to define the terms on and above the diagonal.)

This format will also be useful to build the Simulink model of the robot. Thankfully, the library **onshape-tp-robot** in python can transform Onshape design into an URDF model. It is very important that you have respected the rules explained in the last section. It will download the stl file of each part and create all the joint and the links from the main assemnly. The inertia matrices and the mass are also imported for each block.

As explain on the librairy documentation, you should create onshape API key (see onshape developer portal). It is recommended to store them on your bashrc or zshrc because the secret key will no longer be shown.

```
export ONSHAPE_API=https://cad.onshape.com
export ONSHAPE_ACCESS_KEY=Your_Access_Key
export ONSHAPE_SECRET_KEY=Your_Secret_Key
```

Then, you should create a folder where you want your urdf file to be construct and write a config.json file:

```
~$    mkdir -p robot\_urdf && touch robot\_urdf/config.json
```

The config file must contain at least the following fields :

```
{
    "documentId": "document-id",
    "assemblyName": "onshape assembly",
    "outputFormat": "urdf"
}
```

The documentId is the number (below XXXXXXXXX) you can find in Onshape URL: https://cad.onshape.com/documents/XXXXXXXXX/w/YYYYYYYY/e/ZZZZZZZ.

Once this is done, if you properly installed and setup your API key, just run the following command. It will create an urdf file and put the stl file in the folder.

```
~$    onshape-to-robot robot_urdf
```

The file will contains only the joints define in the final assembly. This is why you need subassemblies with the fixed part. As we can see on the extract below, the camera has a fixed joint with the hand. Also, it downloads all the stl files and describes the visual position of each. However, it has only one global parameter for each subassemblies that define the inertia.


```
<link name="camera">
    <visual>
        <origin xyz="-0.0505004 -3.25261e-18 -0.083" rpy="-3.14159 8.99294e-30 -3.04281e-32" />
        <geometry>
            <mesh filename="package:///camera.stl"/>
        </geometry>
        <material name="camera_material">
            <color rgba="0.282353 0.54902 0.160784 1.0"/>
        </material>
    </visual>
    <collision>
        <origin xyz="-0.0505004 -3.25261e-18 -0.083" rpy="-3.14159 8.99294e-30 -3.04281e-32" />
        <geometry>
            <mesh filename="package:///camera.stl"/>
        </geometry>
        <material name="camera_material">
            <color rgba="0.282353 0.54902 0.160784 1.0"/>
        </material>
    </collision>
    <inertial>
        <origin xyz="-0.003 9.37179e-20 -0.0015" rpy="0 0 0"/>
        <mass value="0.000135" />
        <inertia ixx="5.0625e-10" ixy="-1.00385e-41"  ixz="7.79417e-40" iyy="5.0625e-10" iyz="6.90342e-42" izz="8.1e-10" />
    </inertial>
</link>

<joint name="camera" type="fixed">
    <origin xyz="0.0560004 0.08 -0.0105" rpy="1.5708 3.04281e-32 8.99294e-30" />
    <parent link="hand" />
    <child link="camera" />
    <axis xyz="0 0 1"/>
    <limit effort="1" velocity="20" />
    <joint_properties friction="0.0"/>
</joint>
```

Figure 11: URDF file extract

4.3   Forward kinematics

4.3.1   Matlab simulation

4.3.2   Python simulation

4.4   Inverse kinematics

4.4.1   Matlab simulation

4.4.2   Python simulation

4.4.3   Torque Study

4.4.4   General principal

4.4.5   Joint results

4.4.6   Hardware choices

5 Control

5.1 Open loop

5.2 Closed loop

5.3 Joystick control

5.4 Vision control

6　ROS