ENSTA
BRETAGNE

Submarine hydraulic robotic arm

Tampereen yliopisto
Tampere University

MRG

September 28, 2022

Thomas TACHERON
`thomas.tacheron@ensta-bretagne.org`

Contents

1 Special thanks

I would like to thank Prof. Kari Koskinen, director of the Mechanical Research Group[Gro22] where I carried out my internship, as well as Jussi Aaltonen, my internship tutor and Research Manager, for the welcome and guidance provided.

I would also like to thank the research assistants Tuomas Salomaa, Kalle Hakonen and Eetu Friman who were my "colleagues" during the internship and helped me in the laboratory and in our project.

Thanks also to Prof. Luc Jaulin for giving me the opportunity to do this internship.

2 Abstract

The University of Tampere is a top-class University in Finland and an important research center in Europe especially in Robotics and Mechanical Sciences.

This internship took place in the Mechanical Research Group about the UNEXUP European Project[UNE22b]. UNEXUP is the direct continuation of the European project UNEXMIN[UNE22a]. The objective of UNEXMIN was to design a submarine with a diameter of approximately 60 cm that explores submerged mines. The objective of UNEXUP is to improve the capabilities of the submarine with a view to bringing it to market.

This internship was about creating a robotic arm module with three joints in order to allow the submarine to take samples in the submerged mines. It involved conception, robotic engineering and mechanical engineering. Taking samples is necessary to evaluate the viability of the mine and is therefore a very valuable piece of information.

3 Keywords

Robotic arm, autonomous robotics, submarine, submerged mine, unexmin, unexup

4 Résumé

L'Université de Tampere est une Grande Université en Finlande et un Centre de Recherche important au sein del'Europe, notamment en Robotique et en Sciences Mécaniques.

Ce stage a eu lieu dans le Mechanical Research Group sur le projet Européen UNEXUP[UNE22b]. UNEXUP est la suite directe du projet Européen UNEXMIN[UNE22a]. L'objectif d'UNEXMIN était de concevoir un sous-marin d'un diamètre d'environ 60 cm qui explore des mines immergées . L'objectif d'UNEXUP est d'améliorer les capacités du sous-marin en vue de sa mise sur le marché.

Ce stage consistait à créer un module de bras robotique à trois articulations afin de permettre au sous-marin de prélever des échantillons dans les mines immergées. Il a impliqué de la conception, de l'ingénierie robotique et de l'ingénierie mécanique. Le prélèvement d'échantillons est nécessaire pour évaluer la viabilité de la mine et constitue donc une information très précieuse.

5 Mots-clés

Bras robot, robotique autonome, sous-marin, mine inondée, unexmin, unexup

6 Contextualisation of the internship

The University of Tampere is a top-class University in Finland and an important research center in Europe especially in Robotics and Mechanical Sciences.

Figure 1: Tampere

This internship took place in the Mechanical Research Group about the UNEXUP European Project[2]. UNEXUP is the direct continuation of the European project UNEXMIN.

The objective of UNEXMIN was to design a submarine with a diameter of approximately 60 cm that explores submerged mines. The objective of UNEXUP is to improve the capabilities of the submarine with a view to bringing it to market. The system uses LIDAR technology to map submerged mines. Indeed, in Europe, nearly 30,000 old mines are closed and in the absence of human activity most have naturally filled with water. With changes in the materials market and advances in mineral extraction, it is now possible that the reopening of these mines will become profitable. Moreover, due to the current geopolitical changes, it is desirable to develop independence from mineral imports and therefore to produce them domestically.

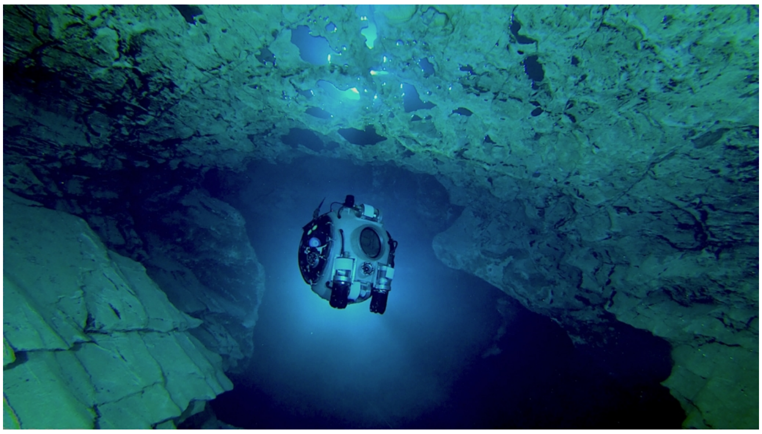


Figure 2: UNEXMIN in a flooded cave [Credit: UNEXMIN GeoRobotics Ltd. (UGR)]

UNEXUP's short-term objective is therefore to gather geological information to help policy makers make decisions at a low cost without the need to pump water out of the mines.

The technological stakes and challenges are such that Europe has become involved in the project, through funding and the cooperation of 13 universities and research centres all across Europe.

7 Internship

7.1 Arm prototype

The work to be carried out consists of designing a mechanical, software (ROS) and electrical architecture for a proof of concept of a robot arm. The robot arm must be adaptable to the UNEXMIN submarine, i.e.:

- capable of operating to a depth of 500 meters,
- on a robot with a mass of approximately 112 kg,
- on a robot which is round and must pass through tight spaces,
- with a maximum power of approximately 150 W.

The submarine and the mapping system are already functional, the aim is to design an arm that can be easily operated remotely in order to take samples.

The materials used are not the final version, and we can consider that the materials used in the future will be resistant to the exploration conditions.

7.2 Work performed

Initially, we had the aluminium part of the arm already assembled without actuators or sensors. The choices made in view of the exploration conditions were the following:

- use of hydraulic cylinders,
- use of a sealed cylindrical container filled with oil,
- design of a 12 V electrical architecture.

It was necessary to:

- model and simulate the robot arm[3] on a computer to study its behaviour,
- design the ROS architecture,
- design the electrical system,
- design the hydraulic system,
- design the sealed connectors,
- calibrate and assemble the sensors,
- design a controller to allow joystick pin-point control,
- design a controller to allow automatic linear movement.

A detailed user and maintenance guide is available in the appendix.

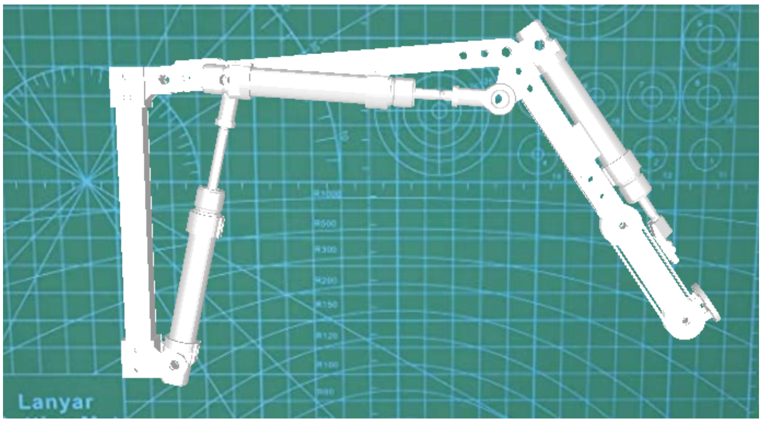


Figure 3: Arm model in CoppeliaSim

7.3 Mechanical and Hydraulic design

To ensure movement in a pressurised environment, we opted for an oil hydraulic system in a sealed container. Three identical modules are designed (one per cylinder) with a backflow prevention assembly.

To ensure movement in a pressurised environment, we opted for an oil hydraulic system in a sealed container.

The architecture of the hydraulics is schematized in the appendix (page 6).

Three identical modules are designed (one per cylinder) with a backflow prevention assembly, and gear pumps made with brushless motors. The aim is to fit all three systems into a Plexiglas cylinder with a diameter of 8 cm. This requires a specific layout and the design of 3D printed separating parts[4].

The system was a source of failure. After evaluation of each parts we found that a gear pump was defective and because we had only ordered three of them, we had to wait for the supplier to send another one, resulting in delays.

For the mechanical design, there are three joints (wrist, elbow, shoulders) operated by three cylinders.

Each joint is angle controlled by hall sensors, so two types of supports had to be designed: one for the magnet and one for the sensor. The angular limits corresponding to the minimum and maximum stroke of the actuators are in the appendix (page 4), the CAD of the robot arm is available in a GitHub repository[TAC22a].

Figure 4: Hydraulics

The design of the hydraulic system required the use of braided lines and penetrating connectors, a list of which is provided in the Appendix (page 9).

The design of the network cable changed the rest of the project. It was necessary to fit an ethernet connector inside the Plexiglass cylinder to ensure watertightness.

However, the penetrating pipe was too thin to allow the 8 wires of the network cable to pass through. The choice made was to reduce the number of wires to 4, which drastically reduced the flow between the submarine and the robot arm.

This made it necessary to optimise the communication between the ROS master (controller of the submarine) and the ROS slave (Olimex micro-controller of the arm).

7.4 Modelisation and Simulation

In order to facilitate the design and software development before the mechanical and electrical design is carried out, we have chosen to model the arm and simulate its operation on the CoppeliaSim software (formerly V-REP) with the Vortex physics engine which is the most efficient simulator with the least error (see page 14 and page 15 of the appendix).

The cylindrical joints are controlled by a lua script and a ROS node specific to the simulation.

The most delicate point is the wrist because it is composed of two pulleys and a belt: we chose not to physically simulate the belt because it leads to too many calculation errors (pieces of belt with very low mass and inertia), we rather linked mathematically the stroke of the cylinder to the angle of the wrist by a lua script.

The simulation thus allowed us to validate the angle conventions and the control of the actuators, as well as the development of the separate control of each joint. The pin-point control was achieved using an inverse kinematics function.

7.5 Electrical design

The electrical system is very simple.

It consists of a 5V BEC to adapt the input voltage, an Olimex controller to host the ROS nodes, a Raspberry Pi Pico microcontroller[BET22] to link the angle sensors, three ESCs and three gear pumps (one for each cylinder).

The detailed system and architecture are in the appendices (page 7 and page 8).

7.6 ROS design

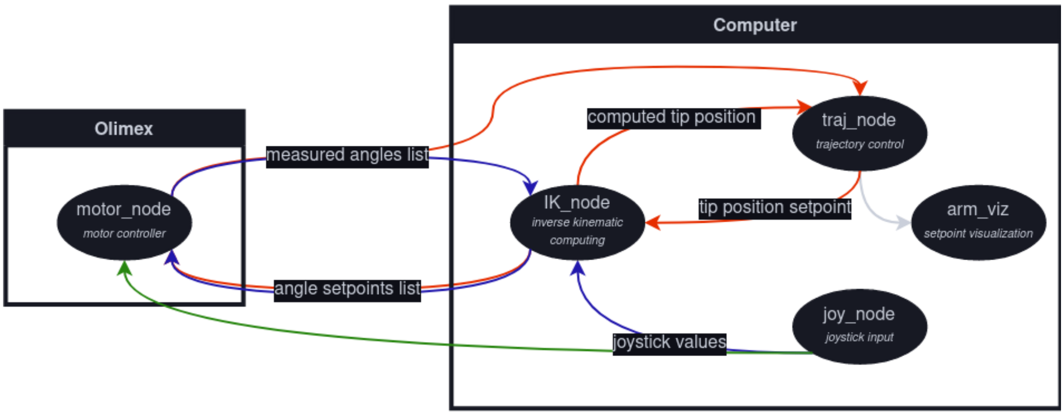


Figure 5: Node graph

The ROS system[TAC22b] consists of five nodes:

- joy_node, a node used to teleoperate the arm with a joystick. The functionalities of this node are described in the appendices (page 11). The available control are: speed control for each joint, angle control for each joint, inverse kinematics or pin-point (control in x and y) and trajectory control.
- arm_viz, a node used to debug and visualize the positions of each part of the arm in 2D. It is however better to use the simulation in 3D.
- traj_node, a node that publishes the setpoint from the measures and the command.
- IK_node, a node that computes the inverse kinematics i.e. computes the needed joint angles given the wanted x and y position of the wrist.
- motor_node, a node that computes the commands for the motors given the joystick command or the inverse kinematic command depending on the control mode selected.

Inverse kinematics function: Receive a desired (x, y) position for the wrist, returns the two corresponding angles $(shoulder, elbow)$. With $A = 260mm$ and $B = 250mm$ the distances between joints.

$$elbow = -\arccos(\frac{x^2+y^2-A^2-B^2}{2*A*B})$$

$$shoulder = \arctan(\frac{y}{x}) + \frac{\arcsin(B*\sin(elbow))}{\sqrt{x^2+y^2}}$$

Due to desynchronisation and communication flow problems, trajectory planning (e.g. Lissajou curve or straight line) was subject to significant delays. Indeed, trajectory planning requires the sending of a list of points and times which is both time and space sensitive. The installation of an NTP (Network Time Protocol) server on the ROS Master to synchronise the robot arm reduced the delays.

However, the insufficient communication rate could not be solved without changing the hardware, which could not be done during the internship. The 4-wire network cable still needs to be replaced with an 8-wire one, which requires a change of the penetrating watertight connectors.

7.7 Results

In the end, the robotic arm is fully assembled and the programs are available on GitHub repositories.

The goal of being able to teleoperate the arm is achieved, with several modes. It is possible to control each joint individually, to point a coordinate (without worrying about controlling all three joints individually), and to plan trajectories.

The trajectory shown in Figure 6 and 7 represents the upper limits of the range of motion possible by the arm. Tracking was performed by following a yellow dot on the arm to assess accuracy.

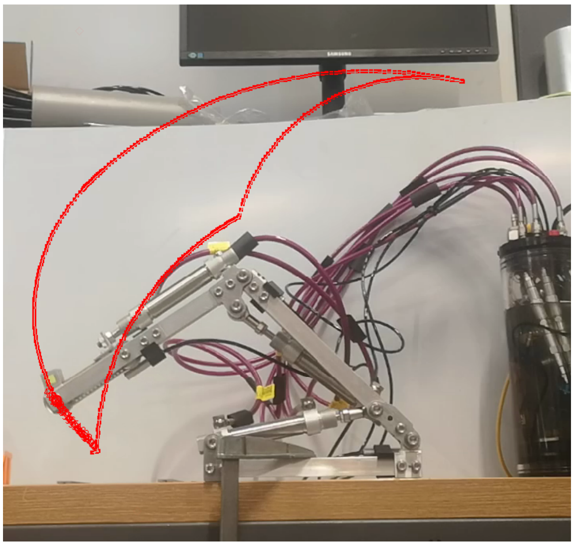


Figure 6: Path planning: Upper limits of the range of motion

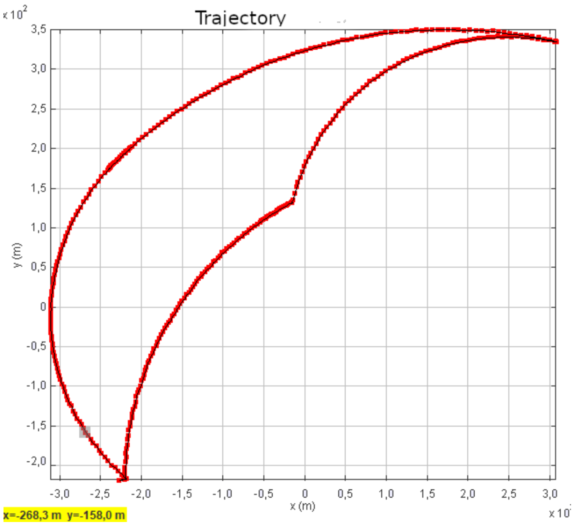


Figure 7: Graph: Upper limits of the range of motion

The maximum error on this trajectory is $e_{max} = 5cm$ and the average error is $e_{mean} = 1.3cm$. These errors are caused by delays due to the reaction time of the system, as well as by inertia effects of the hydraulic system causing overshoot.

The full datasheet of the prototype is available in the appendix. It shows the system architecture, conventions, assembly instructions, user instructions, ROS nodes, simulation instructions and material catalog. It is meant to allow the reader to replicate the project and develop the production version of the arm with adapted and robust materials.

There are still a few things to do:

- change the current network cable to an 8-wire cable,
- choose the tool to be mounted on the wrist,
- compensate for the forces provided by the tool in order to maintain control of the submarine, which may involve adding a force sensor and a new cable to obtain the data (hence the presence of a unused cap in the watertight container),
- create a new ROS node on the submarine in order to transmit the operator's commands to the submarine's onboard computer and then to the arm.

8 Conclusion

This internship allowed me to design an entire mechanical system, combining mechanical, hydraulic, electrical and computer design in an international environment. It allowed me to acquire skills in mechanical design, in particular in hydraulics, which I did not know at all.

This internship is thus quite complementary to my training in robotics at ENSTA Bretagne, in which I had already participated in a design project for an autonomous sailing boat.

In the context of my professional project, it allowed me to gain professional experience that allowed me to plan my work on a long-term project, all day long, whereas until now I had to concentrate on my classes.

This internship also allowed me to develop my knowledge of the English language and to discover working in a European context.

9 Appendices

- Development, Maintenance and User Guide
- Assessment Report

Hydraulic Robot Arm

DEVELOPMENT, MAINTENANCE AND USER GUIDE

Authors:

Thomas TACHERON (thomas.tacheron@ensta-bretagne.org)

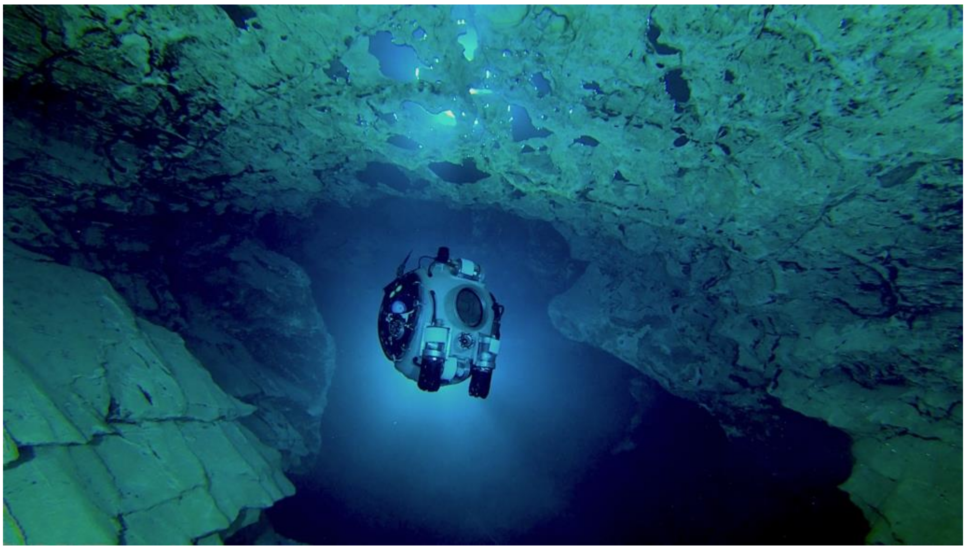
Gabriel BETTON (gabriel.betton@ensta-bretagne.org)

28/07/2022

TABLE OF CONTENTS

Introduction

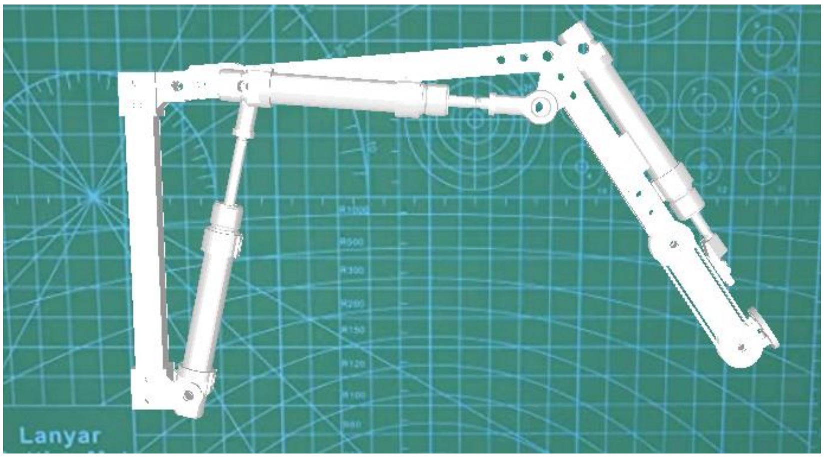
The guide describe the automation of a hydraulic articulated arm on board an autonomous submarine. The project, called UNEXUP, is the direct continuation of the European project UNEXMIN. The objective of UNEXMIN was to design a submarine that explores submerged mines with a diameter of approximately 60 cm. The objective of UNEXUP is to improve the capabilities of the submarine (e.g. by creating a robotic arm module to take samples) with a view to bringing it to market.



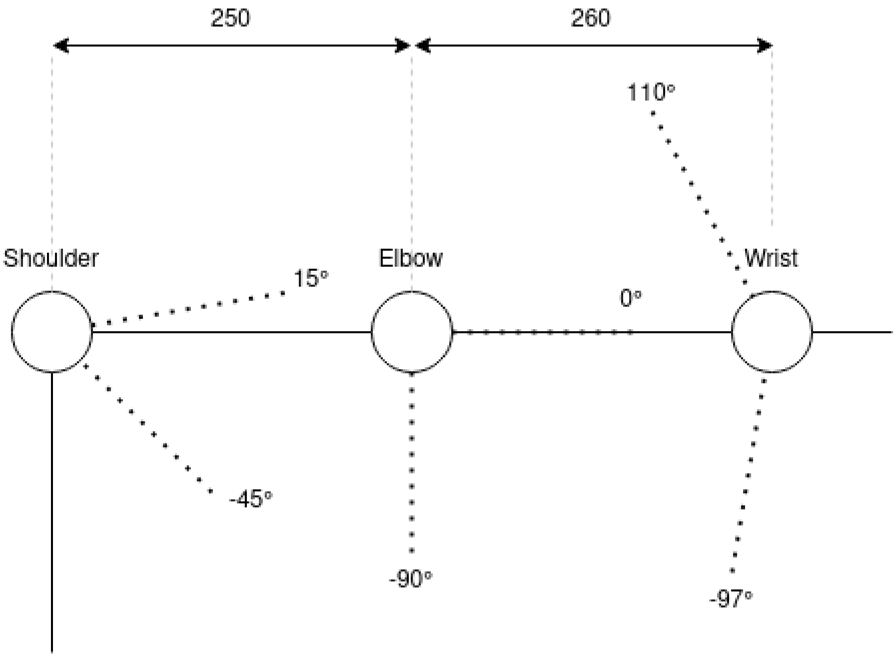
System Architecture

The system is a robotic arm working with a hydraulic system. It is a module for the UNEXUP underwater project.

This guide describes the architecture of the system in order to explore its operation and assembly.

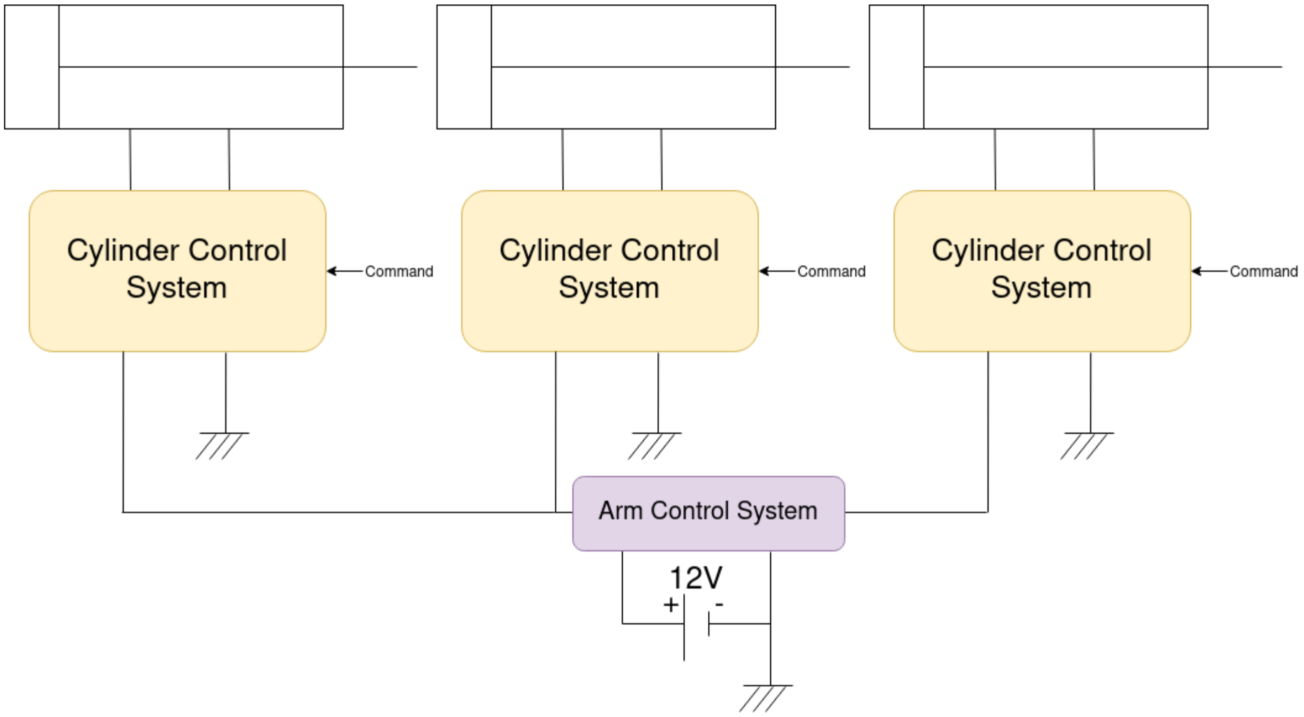


Computer simulation of the robotic arm

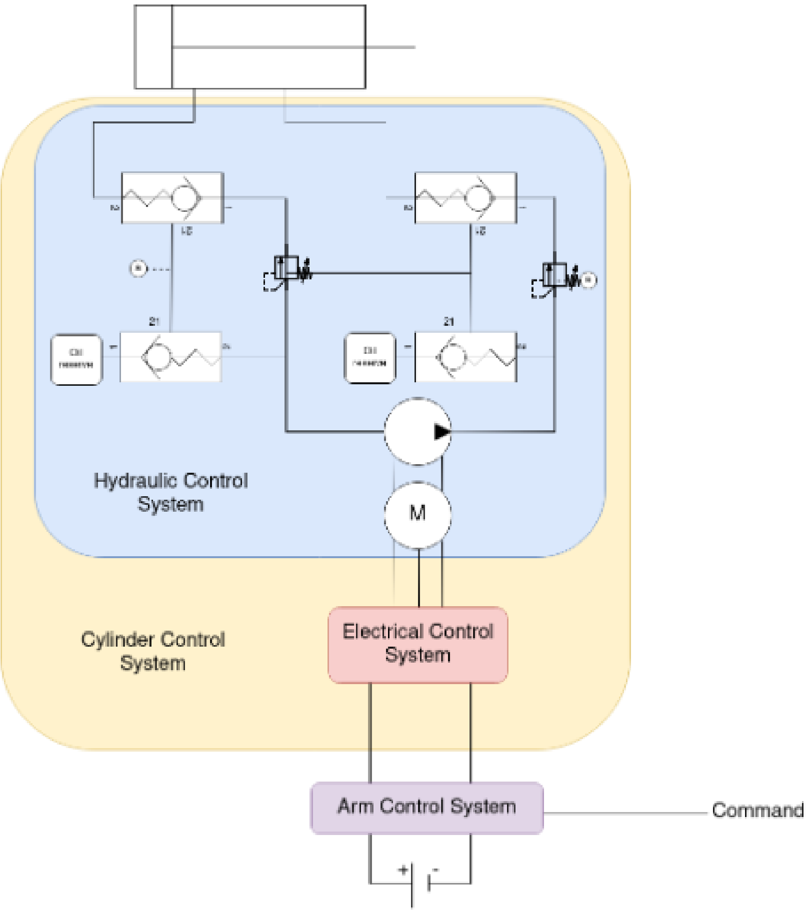


Angular and naming conventions : minimum, maximum and space between joints (mm)

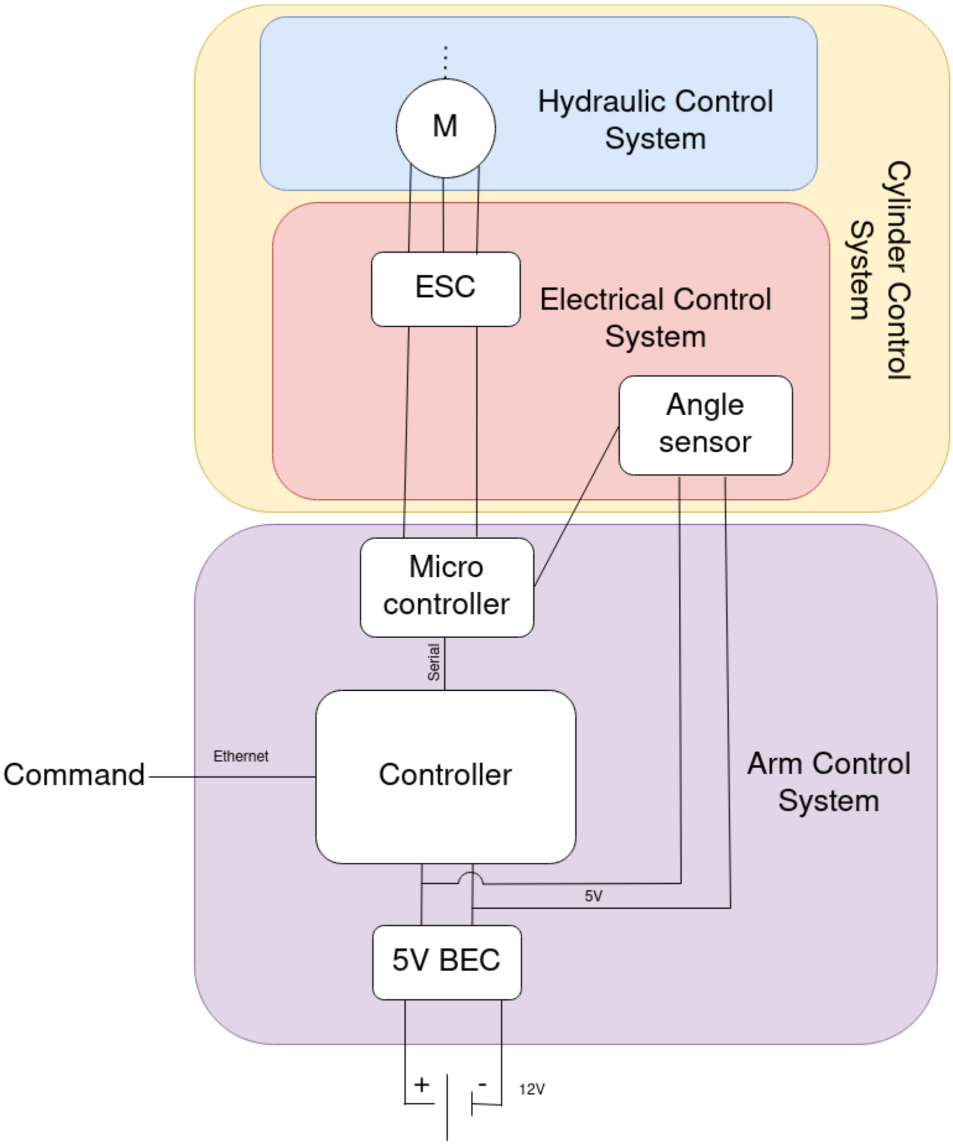
The system is angle-controlled with hydraulic cylinder actuators and angle hall-effect sensors. It uses diverse electrical and hydraulic devices. Here are schematics describing the system.



Overview: 3 cylinders and 3 cylinder control systems linked to another control system

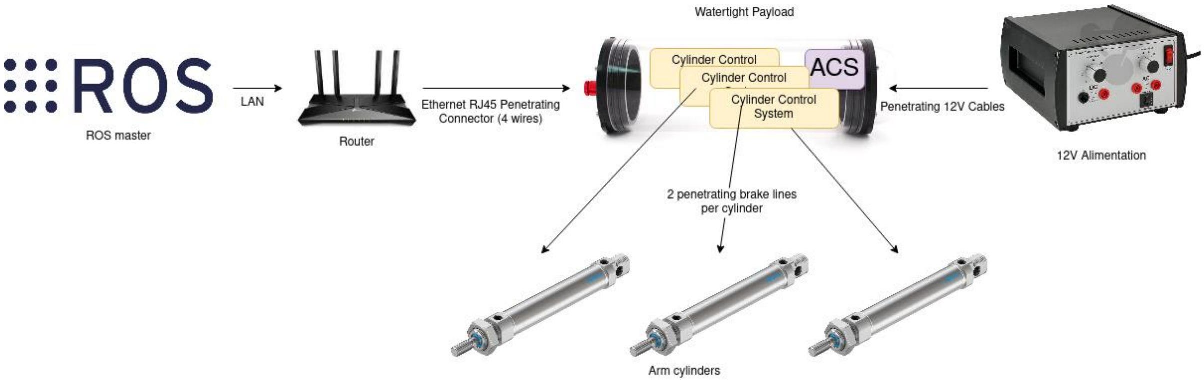


Zoom on the hydraulic control system

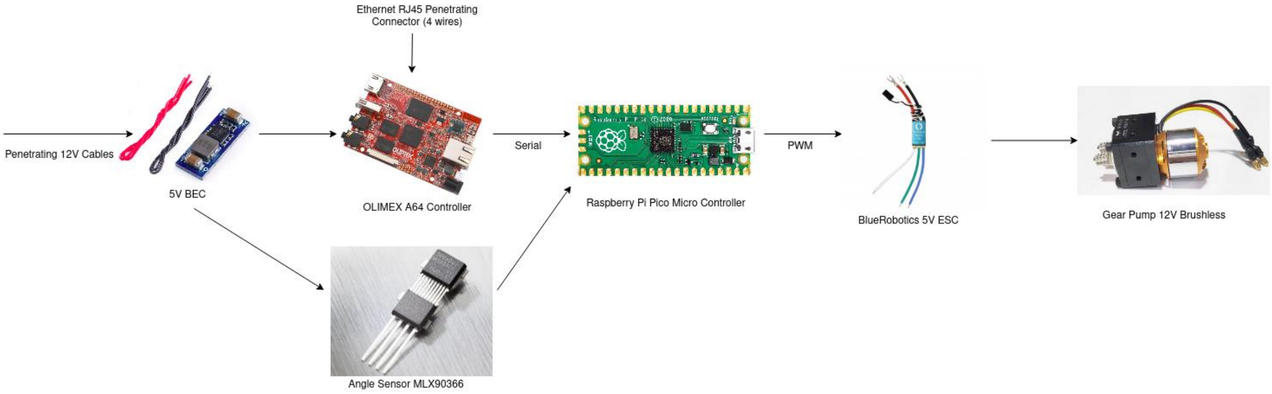


Zoom on one of the three electrical system and the unique arm control system

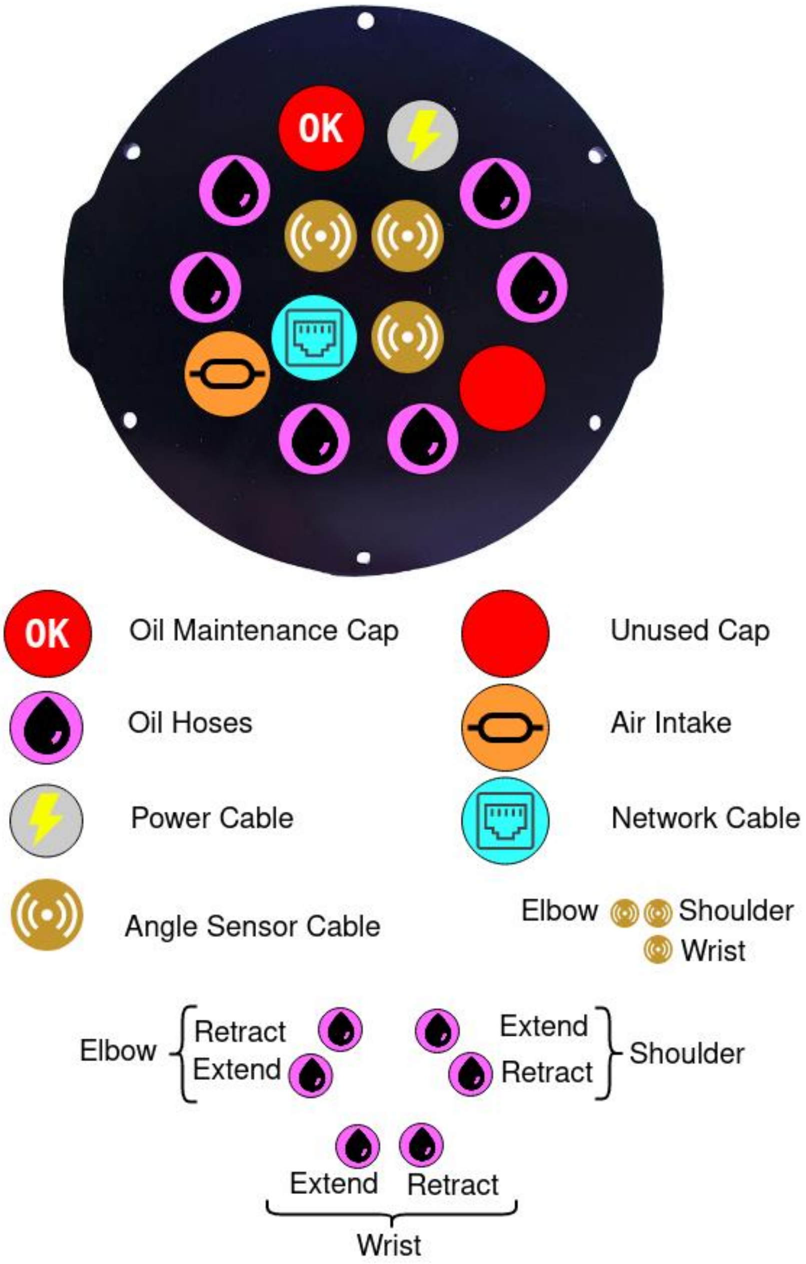
The system needs to be loaded in a watertight container full of oil in order to resist the pressure and the water of the environment. Here are schematics describing the assembly of the system during the tests. To use in real conditions, routers and alimentations must be replaced by the submarines ones.



Overview of the assembly



Zoom on the assembly of one of the three electrical system and the unique arm control system



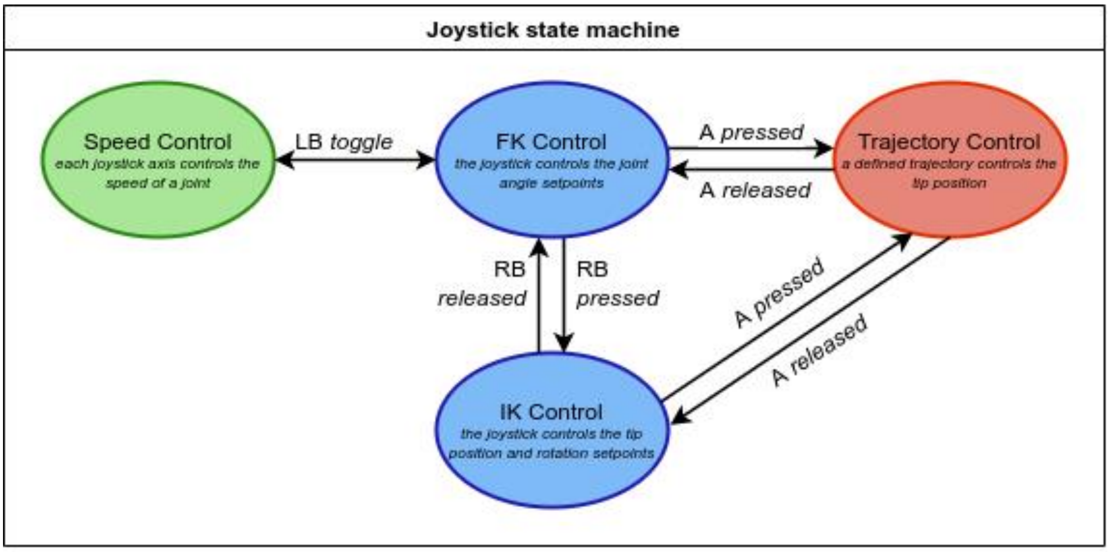
Wiring of the Aluminium Cap

User guide

Setup

- Make sure all the hardware and hydraulic system are assembled (usb connection between Olimex and Pico, all pipes plugged, all ESCs connected, external pipes tightened)
- Power the system with 12V DC (power supply or battery to the external power cable)
- Turn on a router and connect both the system and your computer
- Download and follow the instructions of these repositories :
  - https://github.com/bettonga/hydraulic-robot-arm-ros.git
  - https://github.com/bettonga/hydraulic-robot-arm-pico.git

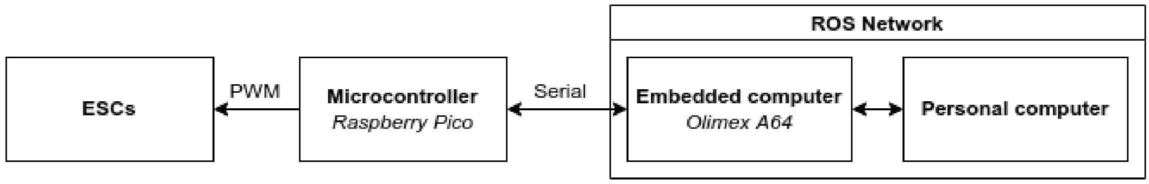
Controls


Joystick state machine
Speed Control
each joystick axis controls the speed of a joint
LB toggle
FK Control
the joystick controls the joint angle setpoints
A pressed
A released
Trajectory Control
a defined trajectory controls the tip position
RB released
RB pressed
A pressed
A released
IK Control
the joystick controls the tip position and rotation setpoints


LB
RB
BACK
START
Logitech
MODE
elbow
shoulder
wrist
Y
X
B
A

Development Guide

Structure



The high-level computing is done by the computers running a ROS network, the embedded computer interacts via serial with a microcontroller programmed for the low-level control of the hydraulic actuators.

ROS files and instructions

https://github.com/bettonga/hydraulic-robot-arm-ros.git

Microcontroller files and instructions

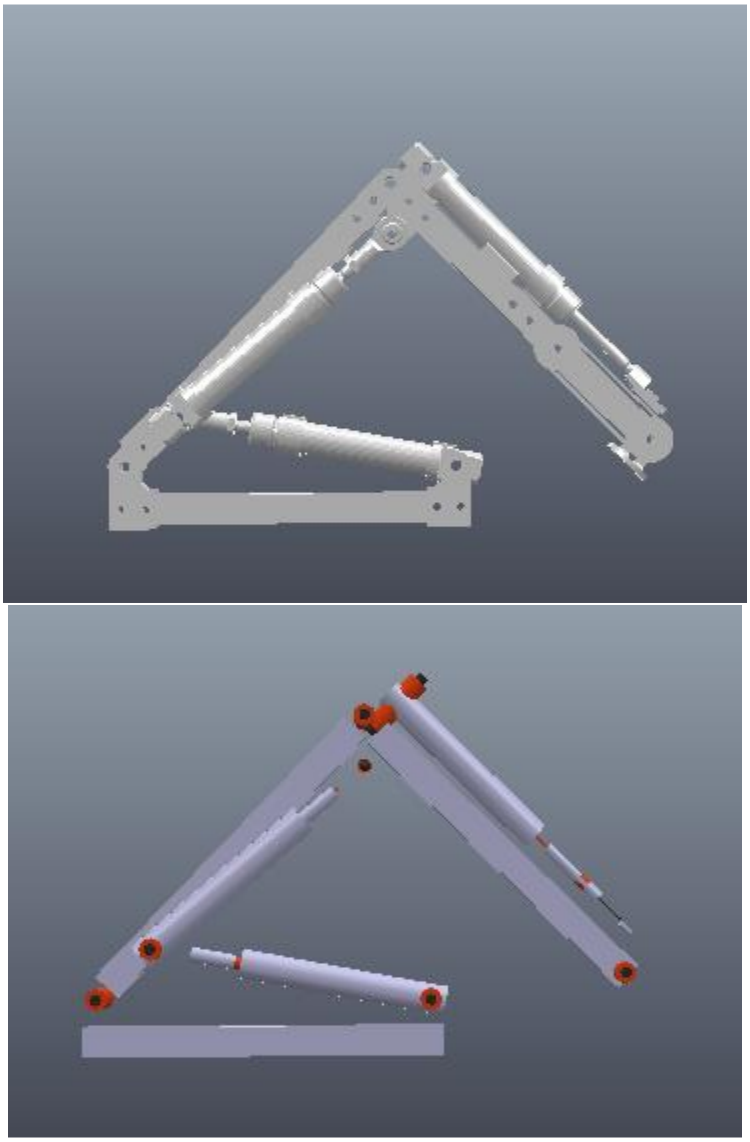
https://github.com/bettonga/hydraulic-robot-arm-pico.git

Simulation guide

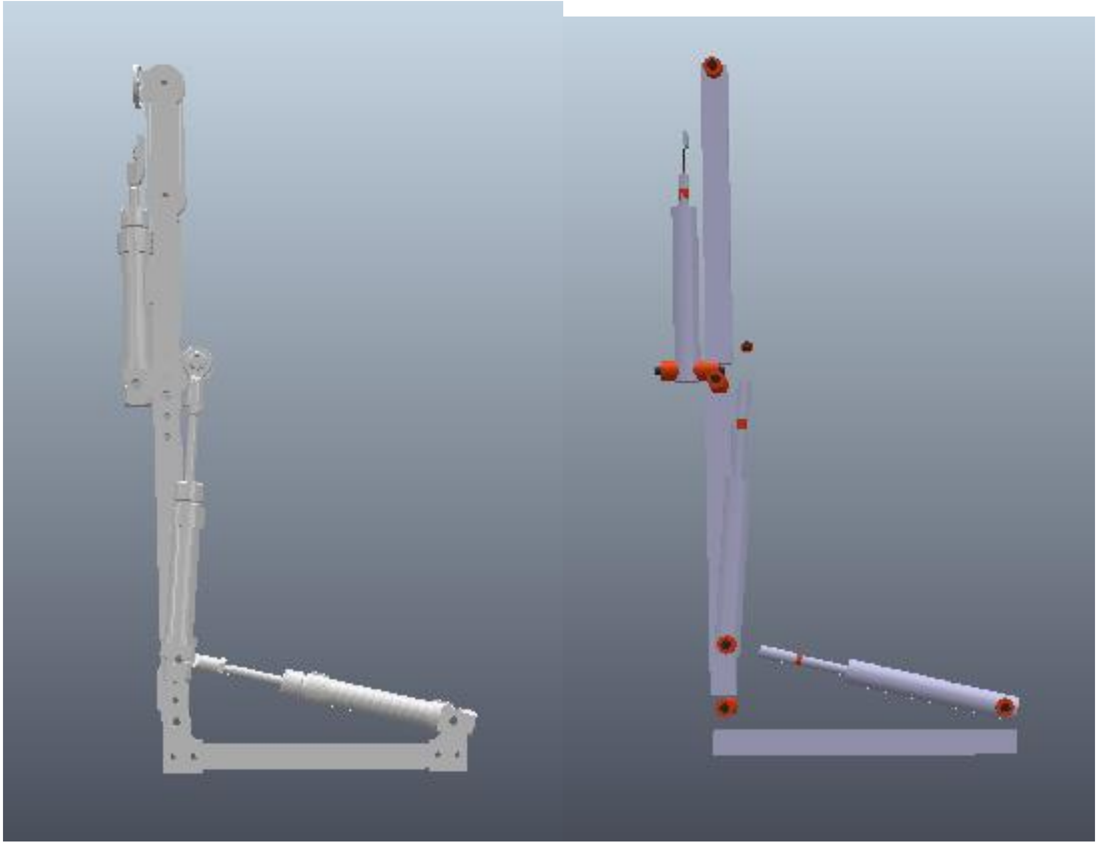
Setup

- The simulation was built on CoppeliaSim for Ubuntu.
- Download Latest Version
- Wrist pulley system is simulated by a lua ROS script.
- Command is entered with a lua ROS script.
- STL models and assembled model are downloadable from the following repository: https://github.com/bettonga/hydraulic-robot-arm-cad
- Launch multiple Linux terminal.
- roscore
- rosrun arm_control IK_node.py
- To use a game controller: rosrun joy joy_node
- Or else use your preferred software.
- Open the model with coppeliaSim (e.g. coppeliaSim.sh arm.ttt).
- Best physics are obtained with Vortex simulation motor. Other motors can decrease the quality.
- **THE MODEL MUST BE OPENED AFTER THE ROS SETUP.**
- Launch the simulation.

Examples

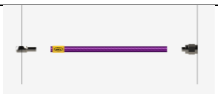


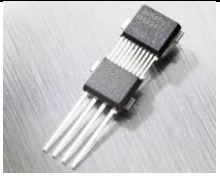
Fully retracted arm (skin only/dynamics only)



Fully extended arm (skin only/dynamics only)

Main material catalog

Description	Picture	Number	Link	+
ISO cylinder		3	Buy on Festo See datasheet	DSNU-20-50-PPV-A Part number: 19237
Basic ESC		3	Buy on BlueRobotics $36	SKU: BESC30-R3 HS Code: 8504.40.40
Custom Braided Brake Lines		6 2*50 2*55 25 30 (cm)	Order on HEL Custom item	Given lenghts are the minimum needed. Add to each line the distance between arm and Aluminum Cap. Suggested: 80 cm
Aluminum End Cap with 14 Holes (4" Series)		1	Buy on BlueROV 36€	SKU: WTE4-M-END-CAP-14-HOLE-R1-RP Category: 4" Series
Aluminum End Cap (4" Series)		1	Buy on BlueROV 20€	SKU: WTE4-M-END-CAP-R1-RP Category: 4" Series

Cast Acrylic Tube – 11.75", 298mm (4" Series)		1	Buy on BlueROV 100€	SKU: WTE4-P-TUBE-12-R1-RP Category: 4" Series
O-Ring Flange (4" Series)		2	Buy on BlueROV 20€	SKU: WTE4-M-FLANGE-SEAL-R3-RP Category: 4" Series
Mini Hydraulic brushless pump M3 with motor		3	Buy on MagomhRC 60€ See datasheet	503002-101
A64 Olimex Embedded Linux Computer with Quad core 64 bit ARM SOC		1	Buy on Olimex 36€ See datasheet	UID BG000042
Piloted non-return valve		12	Buy on Festo See datasheet	HGL-1/8-B 530030
Raspberry Pi Pico micro controller		1	Buy on Raspberry $4	See datasheet
Triaxis® mainstream rotary & linear position sensor IC (SENT)		3	Buy on Melexis See datasheet	MLX90366

Relief valve for Jung pump M5		6	Buy on MagomhRC 30€ See datasheet	503000-352

Pictures and Videos

Joystick-driven mode

Trajectory mode

RAPPORT D'EVALUATION
ASSESSMENT REPORT

Merci de retourner ce rapport par courrier ou par voie électronique en fin du stage à :
At the end of the internship, please return this report via mail or email to:

ENSTA Bretagne – *Bureau des stages - 2 rue François Verny - 29806 BREST cedex 9 – FRANCE*
☎ 00.33 (0) 2.98.34.87.70 / stages@ensta-bretagne.fr

I - ORGANISME / *HOST ORGANISATION*

NOM / *Name* University of Tampere (Mechanical Research Group), Finland

Adresse / *Address* Kalevantie 4, 33100 Tampere, Finland

Tél / *Phone (including country and area code)* +358 29 45211

Nom du superviseur / *Name of internship supervisor*
Jussi Aaltonen

Fonction / *Function* Research Manager

Adresse e-mail / *E-mail address* jussi.aaltonen@tuni.fi

Nom du stagiaire accueilli / *Name of intern* Thomas TACHERON

II - EVALUATION / *ASSESSMENT*

Veuillez attribuer une note, en encerclant la lettre appropriée, pour chacune des caractéristiques suivantes. Cette note devra se situer entre **A (très bien)** et **F (très faible)**
*Please attribute a mark from **A (excellent)** to **F (very weak).***

MISSION / *TASK*

- La mission de départ a-t-elle été remplie ? *Was the initial contract carried out to your satisfaction?* [✓ A] B C D E F
- Manquait-il au stagiaire des connaissances ? *Was the intern lacking skills?* ☐ oui/*yes* ☒ non/*no*

  Si oui, lesquelles ? / *If so, which skills?*

ESPRIT D'EQUIPE / *TEAM SPIRIT*

- Le stagiaire s'est-il bien intégré dans l'organisme d'accueil (disponible, sérieux, s'est adapté au travail en groupe) / *Did the intern easily integrate the host organisation? (flexible, conscientious, adapted to team work)* [✓ A] B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here*

COMPORTEMENT AU TRAVAIL / *BEHAVIOUR TOWARDS WORK*

Le comportement du stagiaire était-il conforme à vos attentes (Ponctuel, ordonné, respectueux, soucieux de participer et d'acquérir de nouvelles connaissances) ?
Did the intern live up to expectations? (Punctual, methodical, responsive to management instructions, attentive to quality, concerned with acquiring new skills)?

[✓ A] B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ____

____

INITIATIVE – AUTONOMIE / *INITIATIVE – AUTONOMY*

Le stagiaire s'est –il rapidement adapté à de nouvelles situations ? [✓ A] B C D E F
(Proposition de solutions aux problèmes rencontrés, autonomie dans le travail, etc.)

Did the intern adapt well to new situations? [✓ A] B C D E F
(eg. suggested solutions to problems encountered, demonstrated autonomy in his/her job, etc.)

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ____

____

CULTUREL – COMMUNICATION / *CULTURAL – COMMUNICATION*

Le stagiaire était-il ouvert, d'une manière générale, à la communication ? [✓ A] B C D E F
Was the intern open to listening and expressing himself /herself?

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ____

____

OPINION GLOBALE / *OVERALL ASSESSMENT*

- La valeur technique du stagiaire était : [✓ A] B C D E F
  Please evaluate the technical skills of the intern:

III - PARTENARIAT FUTUR / *FUTURE PARTNERSHIP*

- Etes-vous prêt à accueillir un autre stagiaire l'an prochain ?
  Would you be willing to host another intern next year? ☒ oui/*yes* ☐ non/*no*

Fait à ______________________, le ______________
In 14th of September 2022, on Tampere

Signature Entreprise ______________________ Signature stagiaire
Company stamp ______________________ *Intern's signature*

Merci pour votre coopération
We thank you very much for your cooperation

References

[BET22] BETTON. See hydraulic-robot-arm-pico repository, 2022. 9

[Bre22] ENSTA Bretagne. Learn more, 2022.

[Gro22] Mechatronics Research Group. https://research.tuni.fi/mrg/, 2022. 1

[TAC22a] TACHERON. See hydraulic-robot-arm-cad repository, 2022. 7

[TAC22b] BETTON TACHERON. See hydraulic-robot-arm-ros repository, 2022. 9

[UNE22a] UNEXMIN. https://www.unexmin.eu/, 2022. 2, 3

[UNE22b] UNEXUP. https://www.unexup.eu/, 2022. 2, 3