Hydraulic Robot Arm

MRG

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Contents

1 Acknowledgements

I first want to thank Prof Kari Koskinen, director of the Mechanical Research Group [Gro22] for approving my internship, as well as Jussi Aaltonen who was my supervisor during my time at the Mechanical Research Group.

I also want to thank my colleagues Tuomas Salomaa, Kalle Hakonen, and Eetu Friman, who were a big help in the lab and our project.

Lastly, I'm grateful to Prof Luc Jaulin for giving me this internship opportunity.

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.

In the midst of the Mechanical Research Group, I was presented with an opportunity to partake in the UNEXUP European Project [UNE22b].
Prior to this project, UNEXMIN [UNE22a] was focused on designing a submarine for the purpose of exploring submerged mines.
UNEXUP is the subsequent step in this process, aiming to enhance the submarine's capabilities and ultimately bring it to market.

Creating a module for a robotic arm with three joints to facilitate sample taking in submerged mines was the focus of this internship.
The goal of this internship was the conception and realisation of both the electrical and mechanical part of the robotic arm.

3 Keywords

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

4 Résumé

L'université de Tampere est une université et un centre de recherche important en Europe, en particulier dans les domaines de la robotique et des sciences mécaniques.

Au sein du groupe de recherche en mécanique, j'ai eu l'occasion de participer au projet européen UNEXUP [UNE22b].

Avant ce projet, UNEXMIN [UNE22a] était axé sur la conception d'un sous-marin destiné à explorer les mines immergées.

UNEXUP est l'étape suivante de ce processus, visant à améliorer les capacités du sous-marin et à le commercialiser.

La création d'un module pour un bras robotique doté de trois articulations afin de faciliter le prélèvement d'échantillons dans les mines immergées était au cœur de ce stage.

Le but du stage était de concevoir puis réaliser le bras robotique.

5 Mots-clés

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

6 Contextualisation of the internship

There is an estimated 30000 closed mine sites in Europe, and these mines still contains valuables materials. As Europe is highly dependant of imported minerals, there is a high interest collecting data on these abandoned sites for potentials re-openings.

However the majority of these closed mines are now flooded and with their complex underground layout, topology and geometry it makes collecting samples by traditional means almost impossible.

This is where the UNEXUP project comes in, a total of eight European organizations are working on this underwater robot that will be completely autonomous and will be able to collect all sort of data in the mines, including high resolution mapping of the site.

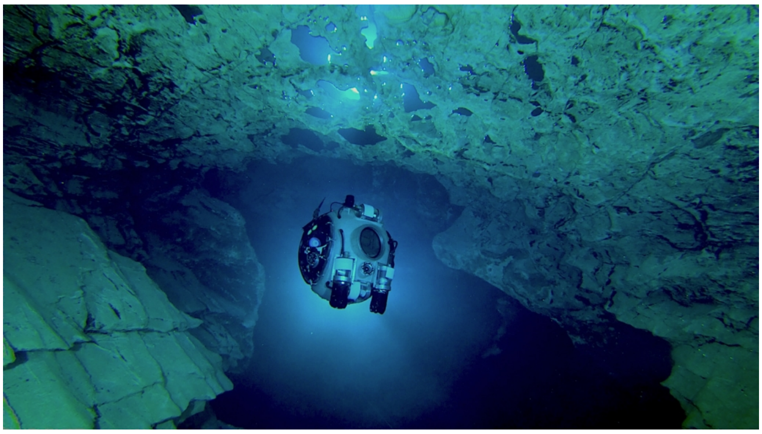

Figure 1: UNEXMIN in a flooded cave [Credit: UNEXMIN GeoRobotics Ltd. (UGR)]

Our mission during this internship was to develop a robotic arm that could be able to collect mineral sample in the mines. So it needed to be precise, strong and able to work in high-pressure environment.

7 Internship

7.1 Requirements

The global idea of the design was already set, the robot arm will consist of an aluminium 3-joint arm actuated by hydraulic linear actuators. The goal was to take care of the control of the robot arm so that it could be connected to and easily controlled by the UNEXUP robot.

Some of the inherited constraints where to be:

- capable of operating down to a depth of 500 meters
- on a robot that navigates through tight spaces
- using a maximum power of 150 W

The materials used were not the final version, and we considered that the materials used in the future would be resistant to the exploration conditions.

7.2 Preparatory work

We began with the aluminium frame of the robot arm, without actuators or sensors assembled. To work in a deep underwater environment, our system had to withstand high-pressure and be water-proof. The solution we chose to work with was to store all the electrical and hydraulic part in a sealed container filled with oil.

The oil would be used to power the cylinders, moreover as it is non-compressible the container would not be crushed by the high-pressure and as a final advantage, the oil acts as an electrical insulator.

Based on these first design choices we then had our to-do list:

- create a model of the the robot arm[3] on a computer simulation software to test the design virtually
- 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 forward kinematic control,
- design a controller to allow inverse kinematic control,
- design a controller to allow inverse kinematic trajectory control.

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

7.3 Mechanical and Hydraulic design

Each one of the three joints are actuated by an identical hydraulic system which consists in a hydraulic cylinder, a gear pump powered by a brushless motor and a backflow prevention assembly. The assembly schematics is in the appendix (page 6).

The entire system fits inside the sealed container, a Plexiglass cylinder filled with oil so the hydraulics work in a close loop with the entry and exit directly in the container.

Only the hydraulic actuators were outside of the container. To send the fluid in and out of the actuators we made the pipes pass through the lid using watertight connectors, as depicted in the appendix (page 9).

In addition of the pipes, the lid was designed to secure the cables coming from the angle sensors, the network cable plugged to the master to control the arm as well as the power cable and an air intake connected to a bladder accumulator for balancing and damping of the pressure.

For that matter, the diameter of the original network cable was too large for the watertight connectors so a thinner one was chosen with a reduced number of wires and as a consequence a slower transmission speed. So this made it necessary to optimize the communication between the ROS master and the ROS slave (robot and robot arm).

One of the biggest challenge was to fit the hydraulic system in the container and letting space for the electrical components (ESCs, Microcontroller, Microcomputer). We made several design before coming to a satisfying one that held everything steadily, without too much material and that was easy to get in an out of the tube [2].

Figure 2: Hydraulics

To keep track of the joints position, hall effect sensors were chosen. These sensors work by detecting the presence and magnitude of a magnetic field, so by using the sensor with a magnet we had an accurate angular sensor that did not required any stator or rotor that could have been damaged by the pressure.

Moreover, as we used an aluminium frame and aluminium hydraulic actuators, the measurements were not disrupted.

We designed parts to hold the magnets in front of the according sensors and 3D printed them. We made sure to design hollowed parts so that water could flow easily through it to withstand the pressure.

7.4 Electrical design

The electrical part of the system is straightforward (see page 7 and page 8 of the appendix), we needed:

- a BEC to adapt the input voltage to the components
- three brushless motors directly linked to the gear pumps
- three ESCs to drive the motors
- three angular sensors to get the joints angle
- one microcontroller to control the motor
- one controller hosting ROS to control the arm

To control the motor, we made a program for the microcontroller for it to be able to control the cylinders according to a message sent by the controller [BET22]. We implemented two operating modes:

- SPEED MODE: to control directly the speed of the motors and thus the speed of the linear actuators, this mode is used for the forward kinematic control where each joint is controlled independantly
- ANGULAR MODE: to control the angle of each joint using a PID loop, this mode is used for the inverse kinematic control where we control the position of the end of the arm and all the joints move accordingly

With the basic of the system working it allowed us to validate the control of the joint and the hydraulic cylinders by the microcontroller thus allowing us to move on the ROS control.

7.5 Modelisation and Simulation

To be able to test our future ROS control without risking any damage on the real arm, we decided to make a virtual model on the CoppeliaSim software, using the Vortex physics engine see page 14 and page 15 of the appendix).

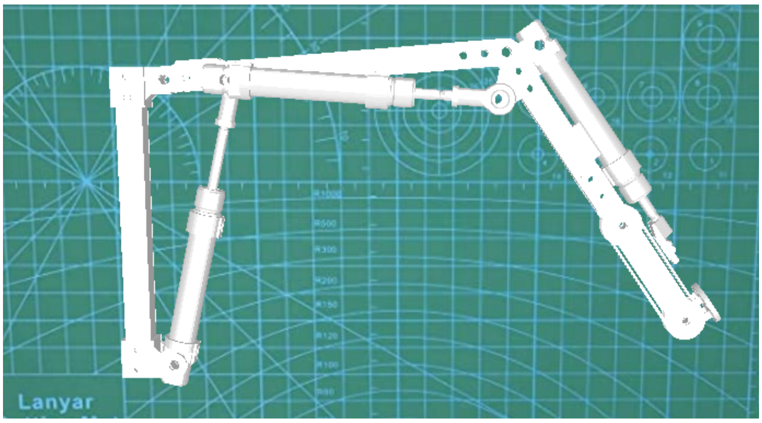

Figure 3: Arm model in CoppeliaSim

We have written a Lua file to act as the microcontroller in the real world, that is to receive orders from the controller then drive the actuators accordingly.

The hydraulic system was not simulated so the hydraulic actuators were controlled directly.

Moreover as the wrist mechanism contains a belt and pulleys we chose to not simulate it either to lighten calculations and errors. Instead we linked mathematically the cylinders length to the wrist rotations using another Lua script.

With some tweaks and improvements on the model and the scripts we made it close enough in behaviour to its real counterpart for us to be able to test our future ROS control on the simulation.

7.6 ROS design

We implemented five ROS nodes for all of our functionalities to work [TAC22b], they are dispatched between the controller within the robot arm system (Olimex in 4) and the computer that will be the submarine in the future.

Each one of these nodes served a purpose:

- joy_node: an interface node to get the values of the joystick. It allowed us to easily control the arm on different modes, a simple state machine of the control is described in the appendix page 11. The goal was to be able to switch between the four control mode, speed control, forward kinematic, inverse kinematic and trajectory control.
- arm_viz: a visualization node used to display the setpoint on a 2D graph to easily compare with the reality.
- traj_node: a trajectory control node getting the actual tip position and setting accordingly the desired tip position for the IK node to compute.

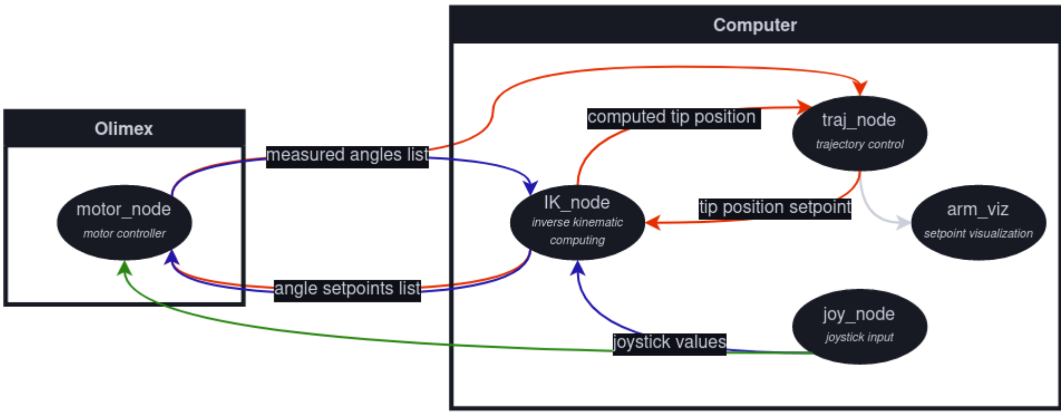

Figure 4: Node graph

- IK_node: an inverse kinematic computing node, getting the desired tip position and setting the desired angle for each joint for the microcontroller to control them.
- motor_node: an interface node to send the value to the microcontroller, it chooses the value to send according to the state of the joystick.

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.

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

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

After this implementation the desired control modes were functional. However a significant delay was observed, it was particularly impractical for trajectory control as it is time sensitive.

We setted up a NTP (Network Time Protocol) server on the ROS Master so that the computer and the controller synchronise in time and it significantly reduce the delay.

7.7 Results

We have managed to fully assemble the robotic arm and the programs are available on GitHub repositories.

The desired modes of control are operational, we are able to control each joint individually, or control the arm tip in a cartesian reference frame as well as giving it a trajectory to follow.

However for now, the microcontroller only control position so the trajectory control is not as smooth as it could be with a speed control loop and better synchronisation and bandwidth.

The speed control is a work in progress, we have implemented a first version to the microcontroller but it needs further testing and improvements.

The trajectory shown in Figure 5 and 6 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.

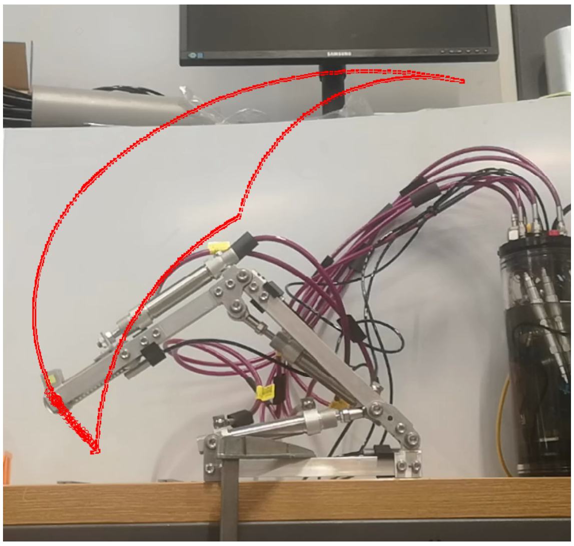

Figure 5: Path planning: Upper limits of the range of motion

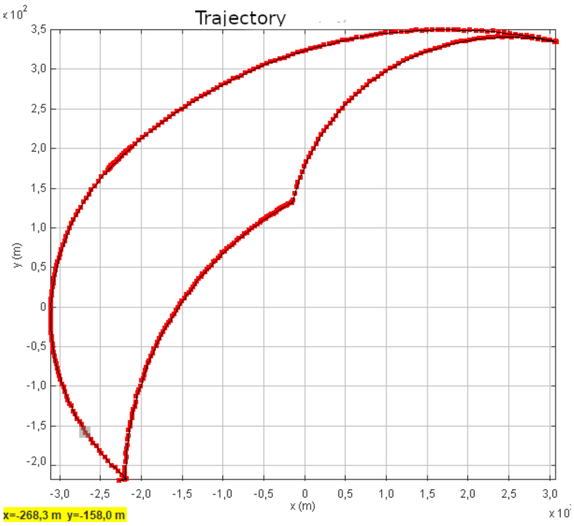

Figure 6: Graph: Upper limits of the range of motion

The maximum error on this trajectory is $e_{max} = 5cm$ and the average error is $e_{mean} = 1.3cm$. We have determined some factors that caused these errors:

- hysteresis nonlinearity: because of our hydraulic assembly, small movements were impossible to achieve, we needed a relatively high speed on the pump to start a movement
- sensor precision: the hall effect sensors were precise but subject to disruption and needed to be calibrated from time to time
- delay in the control loop between the ROS nodes: even with the NTP, the 4-wire data cable was too limiting

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.

The next improvements on the robot arm could be to:

- finish the speed control loop on the microcontroller, it would allow better control on the trajectory
- change the current network cable to an 8-wire cable, that way we could sample more without being limited by hardware
- make a calibrating process for the hall effect sensors
- integrate the system to the submarine

8 Conclusion

I am grateful for this internship to have happened, it has allowed me to put into practice what I have learned during the past year. Refining my knowledge of mechanical and electrical design, low-level and high-level programming as well as learning new ones such as hydraulics which I did not know at that time.

This internship fitted in well with the continuity of the projects carried out at the school, such as the autonomous sailing boat my team and I worked on.

It also allowed me to think about the future of my career, and I really enjoyed working in a research laboratory. I like the idea of working in a team, but I also really enjoy working independently.

This finally confirmed to me that language was not a barrier to teamwork as we all talked in english without misunderstandings.

9 Appendices

- Development, Maintenance and User Guide
- Assessment Report

Hydraulic Robot Arm

DEVELOPMENT, MAINTENANCE AND USER GUIDE

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28/07/2022

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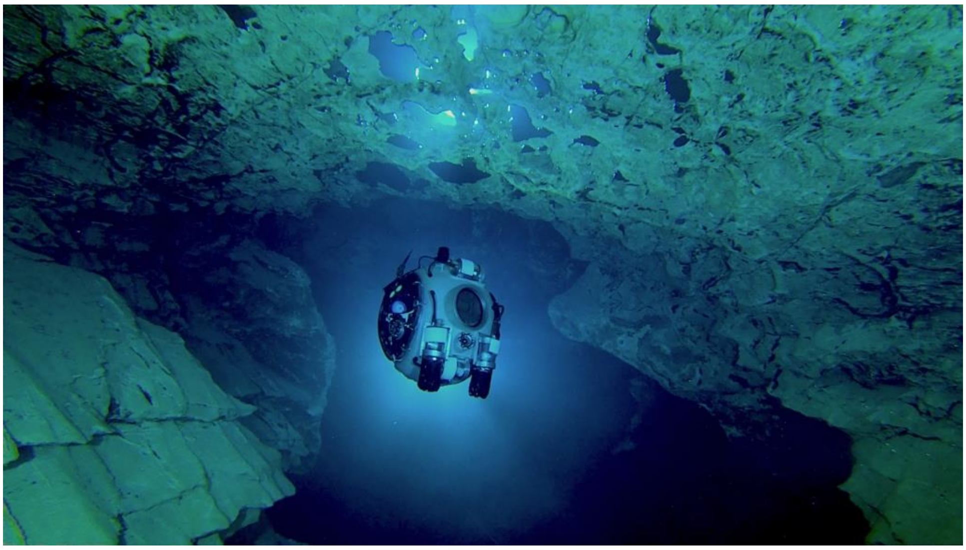
Introduction

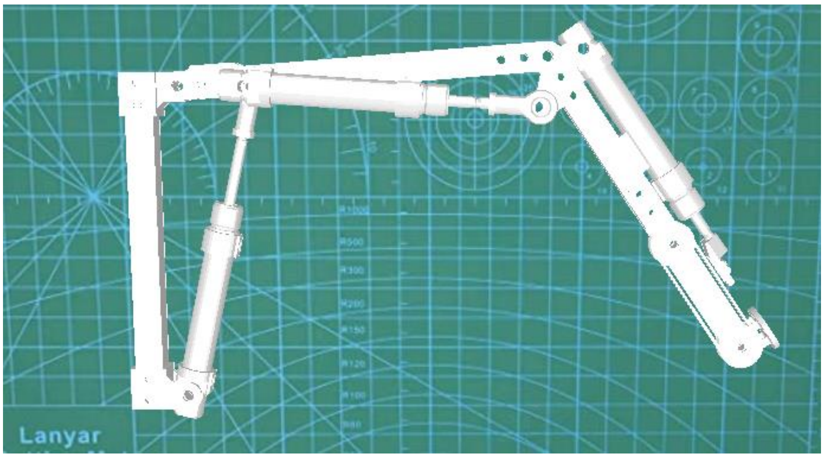
The guide describe the automation of a hydraulic articulated arm on board an autonomous submarine. The project, called UNEXUP, is the direct continuation of the European project UNEXMIN. The objective of UNEXMIN was to design a submarine that explores submerged mines with a diameter of approximately 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.



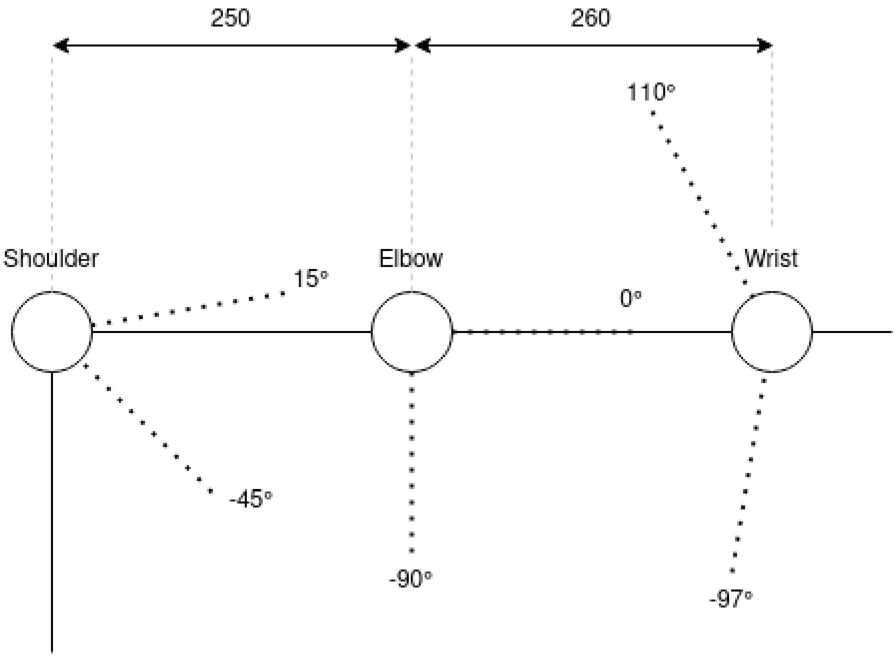
System Architecture

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.

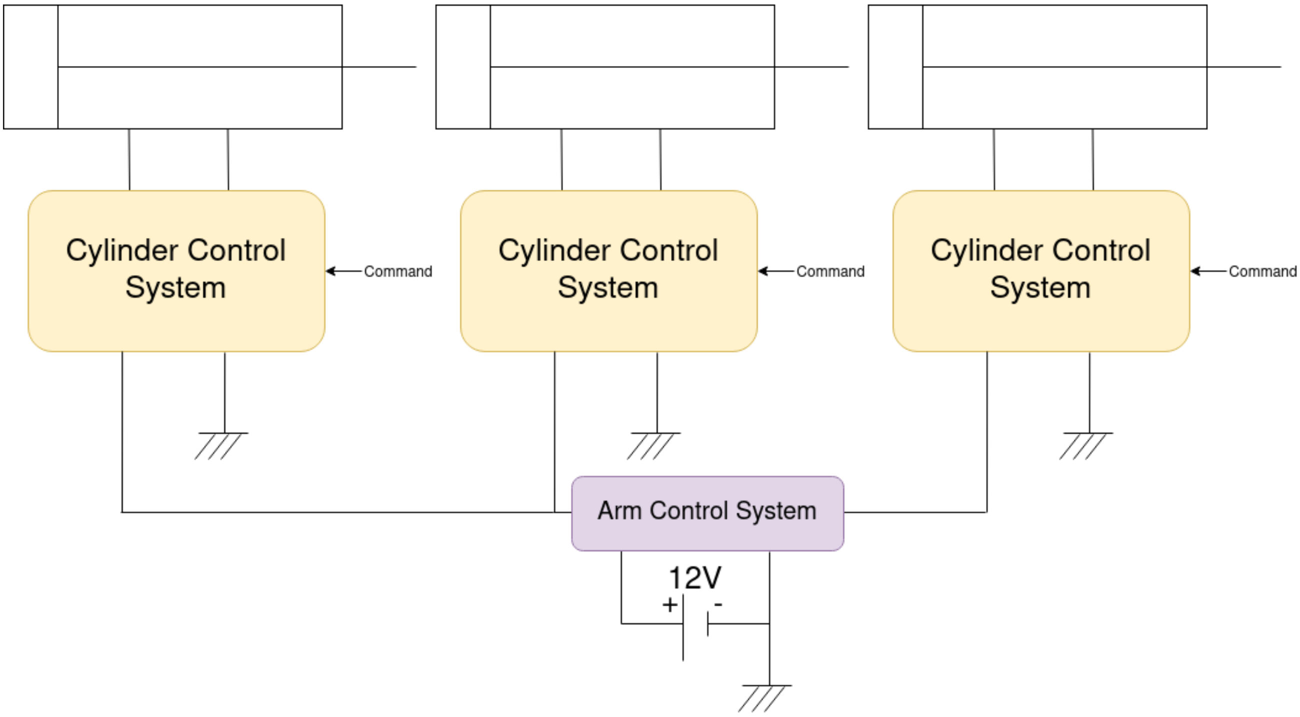


Computer simulation of the robotic arm

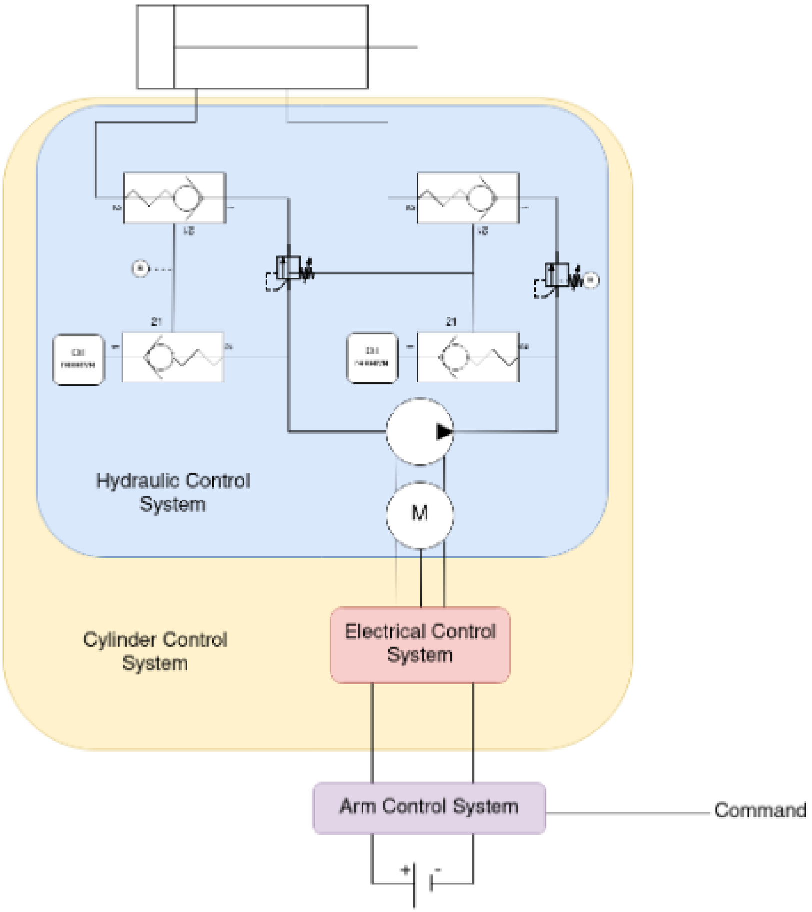


Angular and naming conventions : minimum, maximum and space between joints (mm)

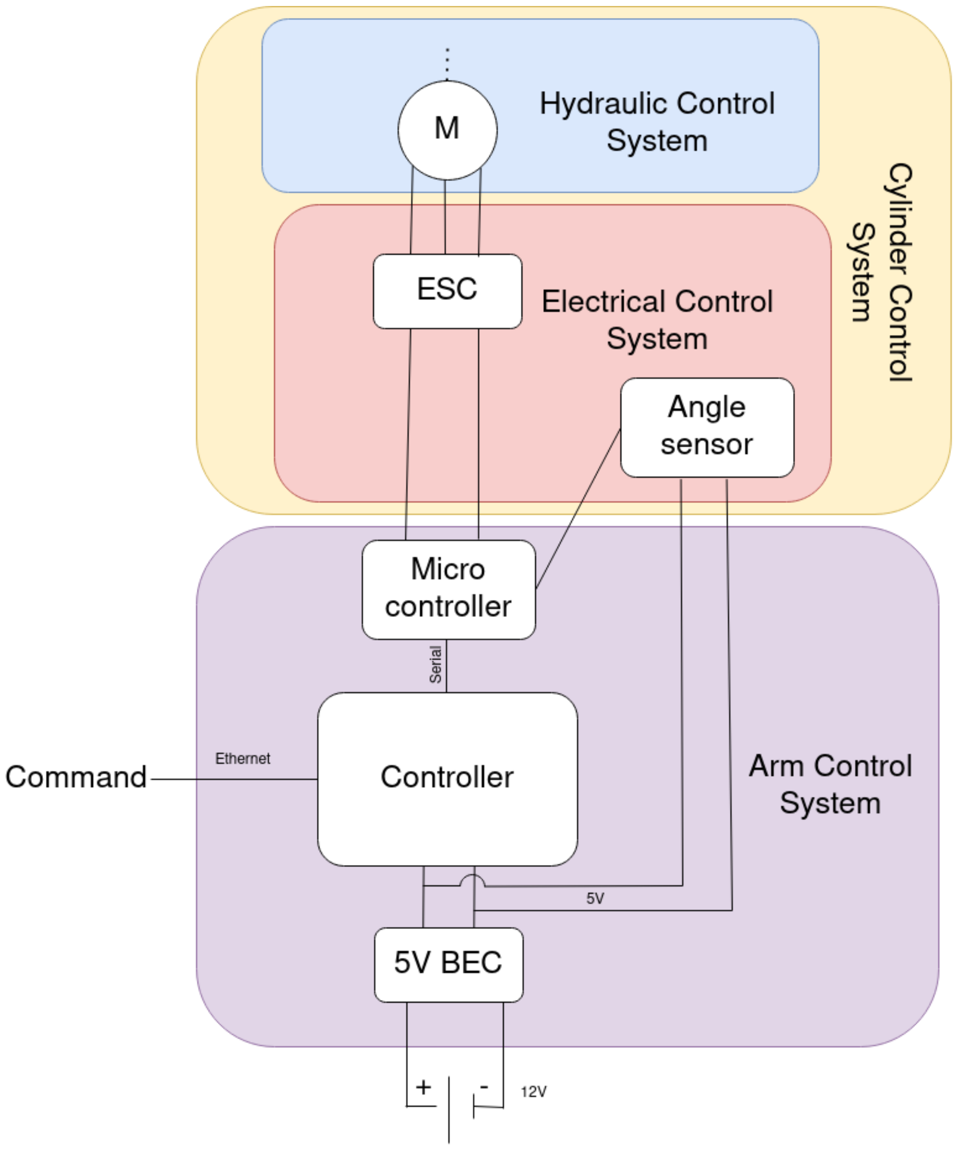
The system is angle-controlled with hydraulic cylinder actuators and angle hall-effect sensors. It uses diverse electrical and hydraulic devices. Here are schematics describing the system.



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

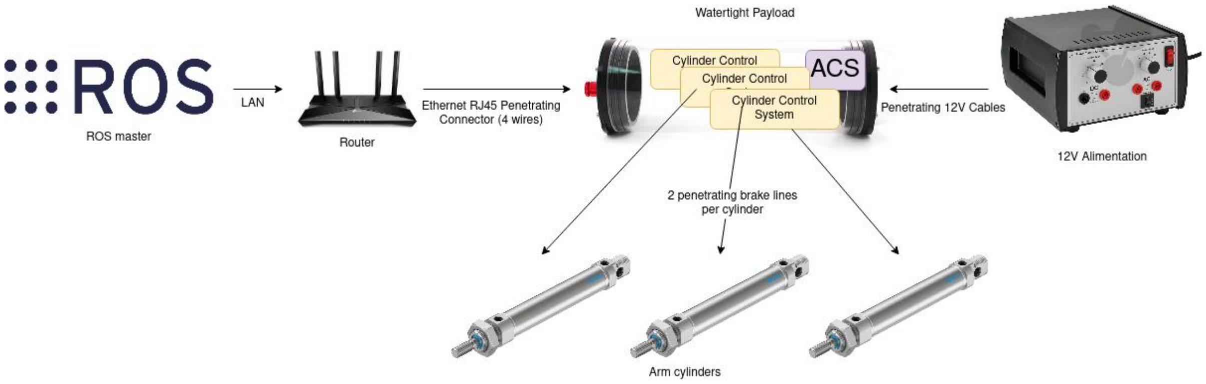


Zoom on the hydraulic control system

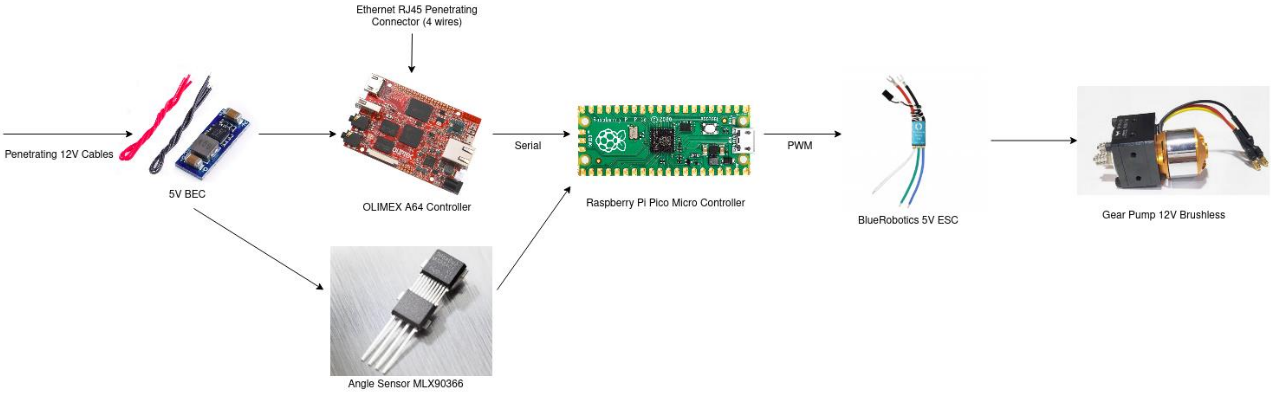


Zoom on one of the three electrical system and the unique arm control system

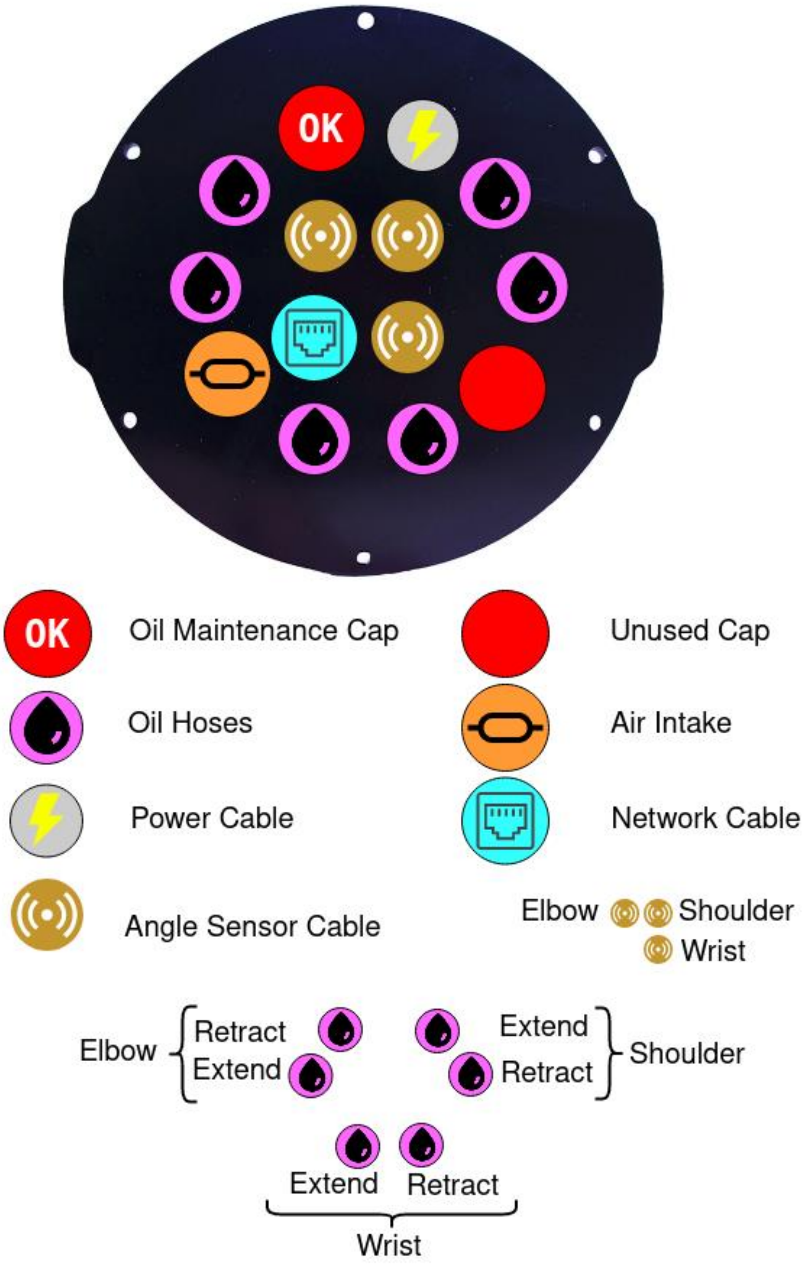
The system needs to be loaded in a watertight container full of oil in order to resist the pressure and the water of the environment. Here are schematics describing the assembly of the system during the tests. To use in real conditions, routers and alimentations must be replaced by the submarines ones.



Overview of the assembly



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



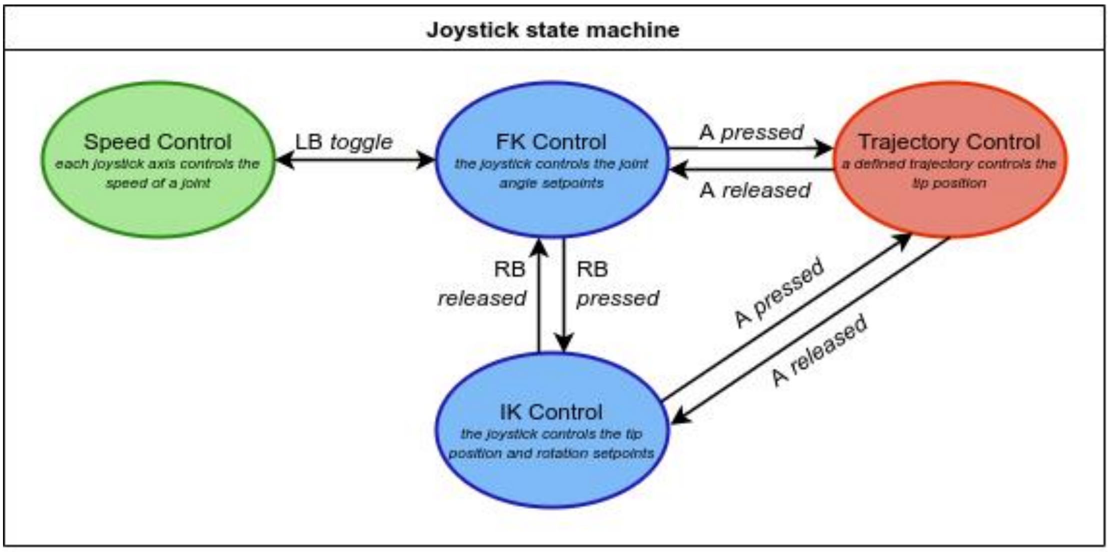
Wiring of the Aluminium Cap

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

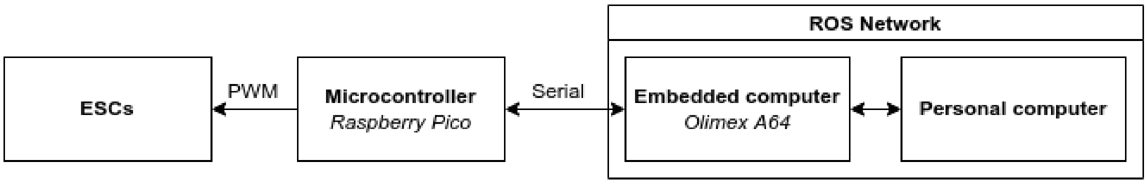
Controls


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
elbow
shoulder
wrist

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

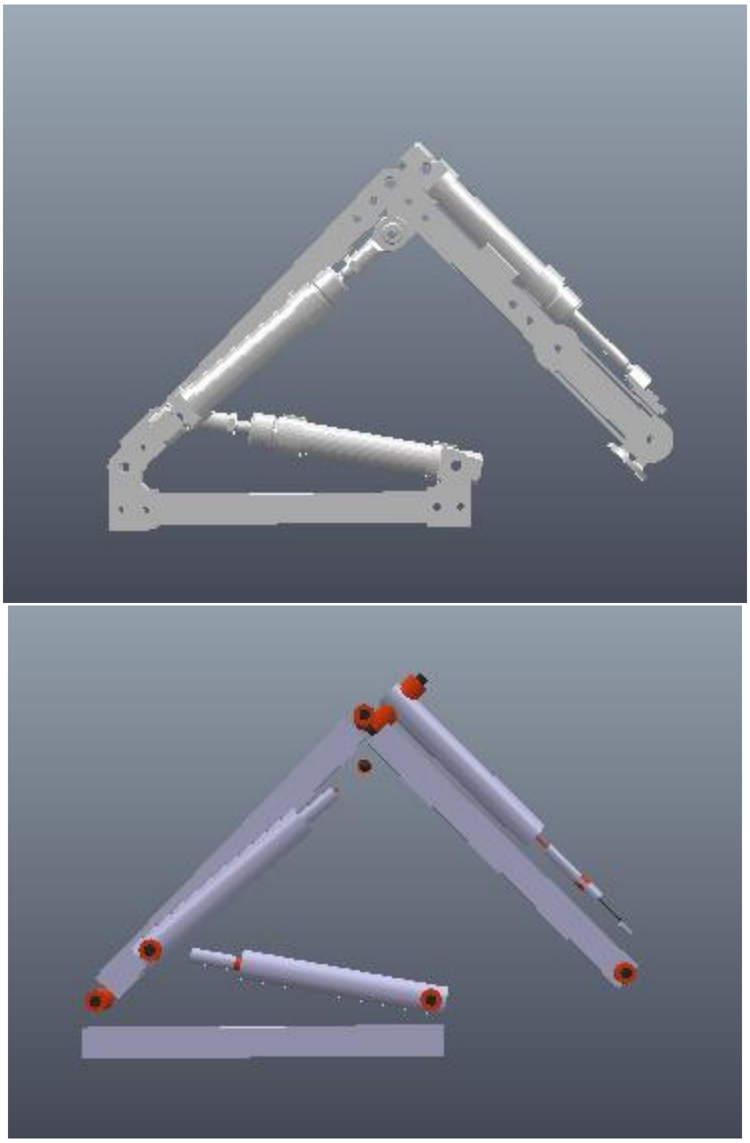
https://github.com/bettonga/hydraulic-robot-arm-pico.git

Simulation guide

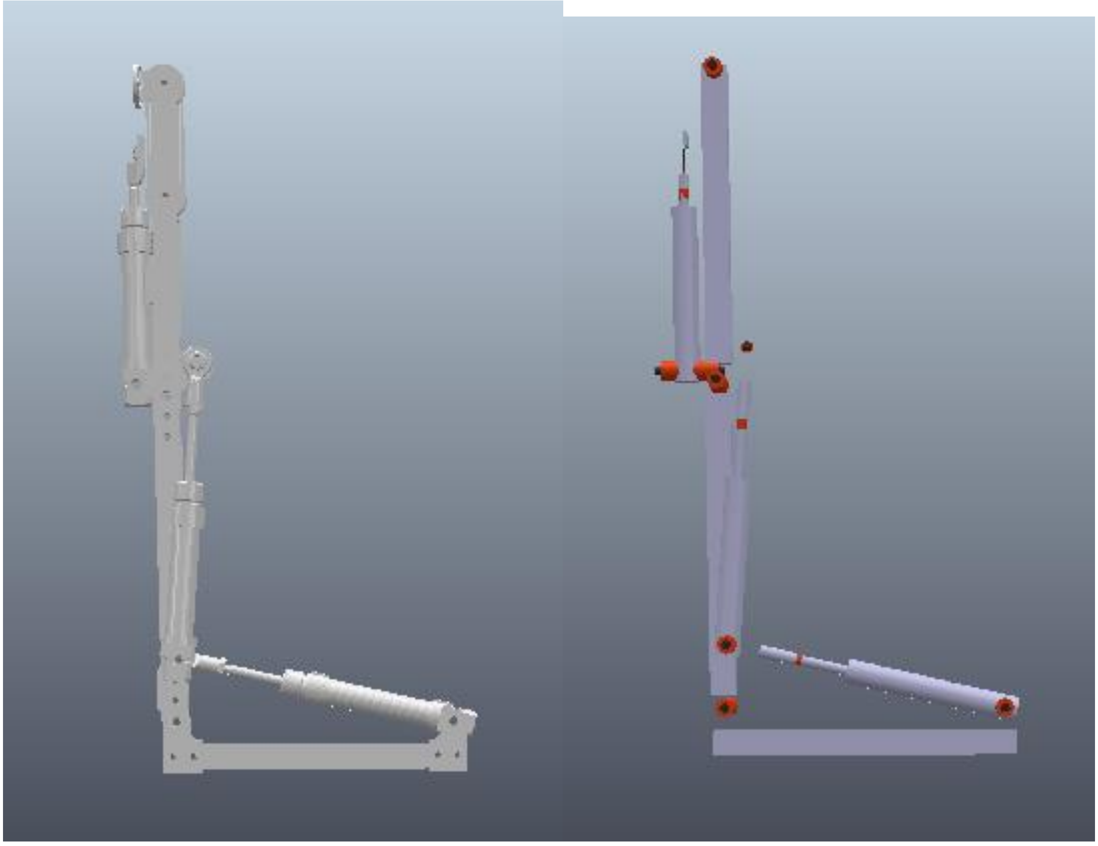
Setup

- 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

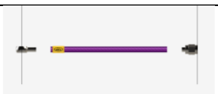


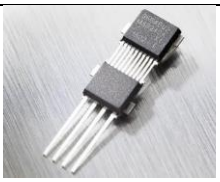
Fully retracted arm (skin only/dynamics only)



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* Gabriel BETTON

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 ? [✓ A] B C D E F
  Was the initial contract carried out to your satisfaction?

- Manquait-il au stagiaire des connaissances ? ☐ oui/*yes* ☒ non/*no*
  Was the intern lacking skills?

  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. 7

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

[TAC22b] BETTON TACHERON. See hydraulic-robot-arm-ros repository, 2022. 8

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

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