



École Polytechnique Fédérale de Lausanne

Open source 3D multipurpose measurement system for
electromagnetic and acoustic field mapping

by Petr Šícho

Semester Project Report

Project Advisor

Daniel Wenz

Project Supervisor

Dimitrios Karampinos

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Abstract

This report details the successful engineering, physical assembly, and customization of the COSI Measure system, an open-source, multipurpose 3-axis robotic platform optimized for large-volume electromagnetic and acoustic field mapping. The goal was to replace the current improvised hydrophone measurement setup with a CNC machine, and also provide versatility of future use. The system provides sub-millimeter positioning accuracy at a fraction of the cost of commercial alternative. This project covers the local revision and manufacturing of mechanical elements, custom PCB soldering, assembly of the machine, devising several upgrades and customization for our use. At the end of the project, the COSI open source hardware guide could be improved based on this build.

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Introduction

1.1 Project Motivation and Background

High-precision multi-axis mapping is fundamental to medical physics and acoustic engineering. The core objective of this project is the construction and optimization of an automatic measurement system capable of supporting a large operational volume to accurately map electromagnetic or ultrasound fields. Traditional commercial multi-axis scanning setups are usually a high cost and not very open to modifications. The COSI Measure initiative provides a low-cost, open-source 3-axis robot capable of delivering sub-millimeter positioning accuracy to replace these expensive alternatives.

1.2 Target Applications and End-Effectors

The versatility of the COSI Measure platform lies in its multi-use end-effector assembly, which can accept various modular attachments depending on the application:

- **Acoustic Mapping:** Interfacing with hydrophone sensors to measure ultrasound fields.
- **Electromagnetic Field Mapping:** Mounting magnetometers, Hall effect sensors, and specialized E-field to map stray fields, characterize gradient or RF coils, and perform implant safety measurements.
- **Subtractive/Additive Manufacturing:** Adapting tools such as a laser engraver, drill or marker for physical crafting and demos.

1.3 System Requirements and Specifications

The platform must achieve a balance between a large active workspace and transportability constraints, ensuring the machine can be moved through standard laboratory doors. The structural and operational baselines for the system are outlined in Table 1.1.

Table 1.1: System Structural and Operational Specifications

Parameter	Requirement
Overall External Dimensions	$80 \times 90 \times 105 \text{ cm}^3$
Baseline Active Working Volume	$? \times ? \times ? \text{ cm}^3$
Target Precision / Position Error	$< 0.2 \text{ mm}$ (Sub-millimeter baseline, TBD)

Building the System

2.1 Mechanical Modifications and Workshop Assembly

The mechanical build process involved adapting open-source design files for specialized local fabrication at EPFL:

1. **Plate Modification:** Technical drawings for the primary aluminum structural plates were completely revised and machined on-site at the EPFL workshop.
2. **3D Modeling and Printing:** The complete 3D assembly models were customized to align with our connectors for motors. Some missing files were modeled (rumba holder, missing mirroring of sensor holder)

2.2 Electronics Fabrication and Interfacing

The electronic subsystem guarantees isolated, low-noise signal routing for precise control:

- **PCB Fabrication:** The primary printed circuit boards (PCBs) were manufactured at EPFL.
- **Component Assembly:** Manual soldering of all surface-mount device (SMD) components was done in the laboratory.

2.3 Hardware Optimization and Custom Upgrades

Several improvements were implemented to enhance the system accuracy and maximize the usable physical space:

- **Dual X-Axis drive:** The X-axis mechanics were upgraded to utilize doubled X motors, aiming to improve structural alignment and positioning accuracy.
- **Component Rationalization:** Selected connectors and routing components were simplified to reduce assembly complexity.

- **Workspace Augmentation via Z-Gantry Rotation:** By rotating the structural orientation of the Z-axis gantry, the physical travel clearance along the X-axis was expanded slight.

Documentation and Architecture

The system was build based on the guide provided in COSI Gitlab repository. Few changes were made where this machine differs from vanilla COSI, that were made either to adapt the machine to our use case, because some components were not easily available and alternatives had to be found, or where we though the original design could be improved upon. All those changes as well as any important notes for the use and maintaining of the machines will be listed in this chapter.

3.1 Mechanical assembly

3.1.1 Upgrades

- We have added one more aluminum profile to the top part of the frame of the machine in order to have a fully enclosed cube with all the 12 edges. This limits somehow access to the machine interior, but also improves the rigidity of the frame. This should help carry the heavy aquarium with water needed for the hydrophone measurement setup.
- The Z gantry was placed on the other side of the long aluminum sheet. This seems to increase the workplace of the machine slightly, as with the other setup the Z axes would collide with the frame when moving too far in the X direction.
- We have decided to use a dual-driven X axis, with a stepper motor on each side. For this we needed to double all the components needed for the X-axis setup (motor, 2x aluminum sheets, threads and bearings, etc.).

All these changes should be visible in the Image 3.1 below, which shows our COSI clone from the top view.

3.1.2 Revisions and Corrections

- In Drawing 9 for the aluminum sheet that is used at the bottom end of the actuator and where the sensors should be placed, there are no holes to attach it. We added 8x M6 threaded through holes and updated the drawing.
- Some number of M6 nuts, M5 and M6 slot nuts, M6x30 flathead and M6x20 countersunk screws are missing from the BoM.

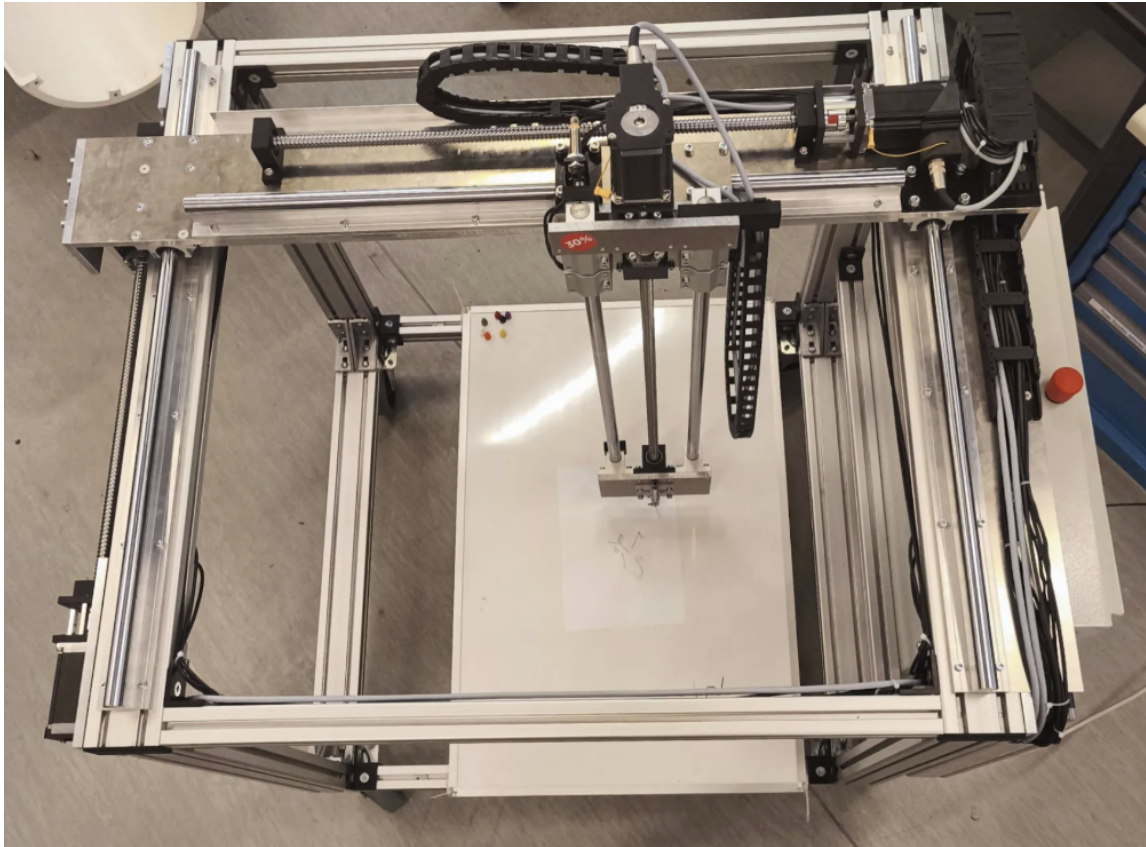


Figure 3.1: COSI mechanical assembly from the top

- The motors we used had a longer axle so that the spacer used were not long enough. We needed to buy a 35mm one instead
- The number of segments of the cable chain was not enough to cover the distance. We have added a piece of aluminum to place the start of the cable chain in the middle, and thus we did not use the provided 3D printed piece.

3.2 Motors and sensors

3.2.1 Servos

This machine uses four motors, two driving the X axis and then one for Y and one for Z axis. Each of them is connected to an independent motor driver and its chassis is grounded. A standard 5-pin connector is used to connect the motors to the electrical control box of the machine. The motor connector and cables are internally connected in such a way that the one coil is on the first two pins, the other coil on the last two and the middle pin is the PE connection. The cables are made with specific length to reach from the motor to the electronic box, but they are in principle interchangeable.

During prolonged operation, the servos can get significantly hot. This should be normal and the servos are designed to handle temperatures up to 130 degrees. During normal use of

the COSI machine, for field mapping, this should not pose an issue as the motors move only momentarily and then measurements take place. However if the machine would be used for another purpose where motors need to move continuously for longer time, the plastic 3D printed casings will need to be replaced, as these are not temperature resistant.

Always check the heating of the motors before leaving the machine unattended!

Heating could also be reduced by completely shutting the motors off during standstill. The COSI is already ready to do this, it just need to be implemented in the program/software. Keep in mind that the motors consume the same amount of current regardless of the speed. Faster move is thus more efficient than prolonged slow move. During idle state, the motors consume about 50 percent of the current in order to lock the position.

3.2.2 Proximity sensors

The proximity sensors are mounted on each end of the axis. The software and hardware sensors use different voltage levels (12V and 24V respectively) and are connected to different parts of the electrical box. The sensor box, as was shown in the guide, was not used, instead the sensors are connected directly to the electrical box. The software sensors are currently not used for anything, but in the future it is envisioned to use them for automatic homing (thus the machine will be able to perform repeatable movements, as the coordinate system will be tied to the sensors and not to the point where the machine starts, even at power loss and when the axis are moved manually by accident). The Rumba board has connection only for 6 sensors, but we only need to connect one end of each axis where the homing will be performed. The other software ends will be calculated in software based on the size of the workspace

The sensors can be moved around to reduce the workspace in order to protect something sensitive inside of the machine. This is the easiest way to protect an area. Other way would be to use automatic homing and then define the allowed workspace in software. This would be the way to go in the future as this does not need any adjustment of the machine.

3.2.3 Safety Systems

The COSI has by default several safety mechanisms to protect the user and the machine itself. These protection mechanisms are detailed in Table ???. These mechanisms are implemented in the *XPSUDN13AP* safety relay, which will turn off all motor drivers in case any of the mechanism trips. This, however, does NOT shut the control board nor any of the low voltage electronics.

The operational status of the safety relay is indicated using a white light on the ON/OFF button on the side of the electrical box. The machine is operational when the light is on. In case of the relay triggering, it will need to be reset using the OFF button or the emergency shutdown button. After that the machine relay will need to be activated again using the ON button, after which the white light will shine again.

If you want to shut the machine down completely, rotate the master power switch on the lower part of the side of the machine. This is the only way to turn down even the low voltage control parts (Rumba and RPI).

There are also two circuitbreakers, protecting the 24V line for the motors and the 5V line for the control boards against short circuit. These should never trigger during normal operations and if that happens a severe electrical problem is to be suspected.

Emergency Cut-Off

Physical safety kill switch on the top of the electrical box

Press in order to avoid imminent collision or prevent unwanted motor move. In order to reset, pull the button up using force.

External safety connector

There is an external safety connector, that allow to connect another emergency shutdown that would be farther away from the machine.

The connector is now wired closed in the WAGO connectors marked "stop". This connection will need to be removed in order for the external stop to function.

Motor Monitoring

Overcurrent and phase loss protection in the motor drivers that ensures that the motors are working correctly, are not exerting too much force and are not losing steps.

This could sometimes be triggered even during normal operation, maybe because the force was higher or axis was binded slightly. The usual symptom is that only one or two of the motors stop moving, but the safety relay is still open, the affected motor driver will also blink with red led. Reset the safety relay in order to clear the error.

Endstops

Dual software and hardware inductive endstops are installed at both ends of every axis (16 in total). The software endstops are first triggered which should communicate to the Rumba that we are at the end of the workplace. If Rumba does not react and moves further, the hardware endstop will trigger, shutting the machine down.

In order to correct this state, the axis will have to be moved manually back in limits (or the sensor holder temporarily bent away - this is useful for the X axis, as moving both of them by hand is challenging)

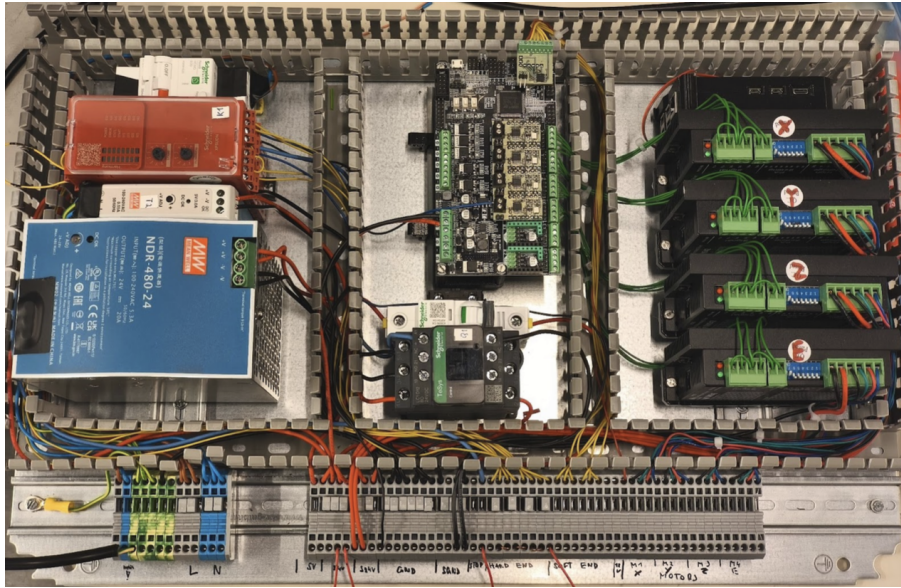


Figure 3.2: The electronic compartment of the COSI machine

3.3 Electrical box

The electrical box houses all the components of the control, driving, and safety systems of the COSI. It was built according to the guide with some small changes listed below. The connector panel of the electrical box was completely reworked to fit on the removable plate of the case and also to have one connector for each of the sensors instead of using the 10-pin connector for the sensor box.

- External hardware connector is hardwired closed as it is not used at this time. To use it, remove the jumper between the two WAGOs labeled "STOP".
- The Rumba 3D enable pin is wired to the normally-open pin of the safety relay instead of the normally-closed as said in the guide, which is probably by a mistake.
- The driver pins are labeled differently in the guide than what are the pins on our drivers. The 2B pin is switched with 2A
- The secondary motor on the X axis is wired into the E (extruder) motor driver and Rumba port. This axis is then mapped in software to mirror commands send to the X axis.

The inside of the electronics cabinet is visible on Image 3.2 below. Every component is connected to the WAGO connectors that are marked, so no soldering was needed. Only the connectors are soldered to jumpers and common ground and voltage rail. The main control board is Rumba 32, which is directly controlling the motor drivers. A micro USB port is used to communicate with it. There is also a Raspberry PI computer, which has its connectors routed to the panel on the outside of the electronics compartment, to allow for easy access.

3.4 Software

3.4.1 Firmware Configuration and Marlin Framework

The Rumba runs standard Marlin 3D printer firmware, allowing it to parse GCODE commands. This maintains plug-and-play compatibility with legacy hydrophone software and is very general to allow for future use of the machine.

The Marlin configuration files were changed and recompiled to support the dual X-axis motor upgrade, set with the proper mm/step distances and speed limits for the steppers.

The imaginary zero of the coordinate system is set to the top corner, where all the cables are going to the electronics box. Moving in the positive direction of the XY axes means moving away from this point. The Z axis is defined with the positive direction being up and the negative direction being down. In order to assign a point where the machine is currently as the origin (point 0,0,0), you have to run the “G92 X0 Y0 Z0” command. This should be done before every measurement using the legacy hydrophone measurement. The commands can be send using any standard GCODE sender or CNC/GRBL control software (Candle, Pronterface...). The machine can be operated in either relative (“G91”) or absolute mode (“G90”). Moves are performed in both cases using the “G1” command and setting the X,Y or Z parameters to some value, while speed/feedrate is set using the F parameter. Normal operating speeds range from 100 to 600, and the speeds affect the noise levels. I recommend using the higher speed as not to unnecessary heating up the motors (more in section about motors), if some noise is not an issue. All the command that can be used with the machine are described in detail in documentation of the Marlin firmware.

3.4.2 Motor driver control

The are custom made PCBs that allow the complete shutting down of the motor drivers from software. The pins can be controlled using the GCODE “M42” and using the correct pin number. In order to turn on the motor driver on X axis, you would for example have to execute the command “M42 P46 S0 T1“. All the pins are detailed in the table below.

	X1	Y	Z	X2
Pin	PC14	PE4	PE0	PC13
Gcode	P46	P68	P64	P45

Table 3.1: Pin assignments and corresponding Gcode pin numbers.

3.4.3 Future upgrades

The original COSI guide recommends the Klipper firmware to be used on the RPI, which is more powerful than the current Marlin, but is also slightly harder to use. This would be one future upgrade of the machine, as the RPI computer is not currently used and it relies on an external computer to send GCODE commands to Marlin. With Klipper and RPI, the

whole machine could be independent, which would allow use even outside of a laboratory (for example, near a MRI machine)

Conclusion

4.1 Proposed Characterization and Validation Framework

To transition the machine into active laboratory service, the next immediate phase focuses on rigorous physical validation:

- **Precision Testing:** Mechanical tolerances were be mapped by mounting a carbide scriber to create physical indentations on a test plexiglass surface. Measuring the spread of distances across repeated iterations will determine the true positional variance. This was determined to be below error caused the measuring capability we had using a standard caliper and size of the holes. The accuracy of the machine in the XY was determined to be about 0.2 mm.
- **Further testing:** More precision testing will be performed using a 1-micron dial gauge to properly characterize the precision of the machine. Repeatability of position will also be measured.

4.2 Concluding Summary

The implementation of the COSI Measure platform provides a highly versatile, economical, and precise alternative to proprietary laboratory scanners. Through localized mechanical machining, custom electronics fabrication, and key structural modifications—such as dual-motor tracking and gantry rotations—this build successfully expands the capabilities of open-source instrumentation at CIMB. Future precision validation steps will finalize this machine as a high-fidelity lab instrument.