Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Institut für Integrierte Systeme
Integrated Systems Laboratory

Department of Information Technology and Electrical Engineering

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# Multi-Sensors Control System for a Transportation Vehicle in a Low-Pressure Environment

Bachelor Project

swissloop

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# Acknowledgements

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# Abstract

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Carl Friess,
Zurich, 25 August 2018

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Chapter 1

# Introduction

The Hyperloop Passenger Transportation Concept was initially proposed by Elon Musk in his Hyperloop Alpha paper[1] as an alternative to the planned high-speed rail project connecting San Francisco and Los Angeles. The argument was, that the high-speed rail project was not the state of the art in terms of technology, much too expensive and significantly slower than other high-speed trains around the world. The objective of the Hyperloop is to achieve passenger transport on the ground over long distances at speeds exceeding 1220 km/h.

To achieve such high speeds, pressurized passenger capsules ("pods") would run in tubes where a vacuum is maintained. The initial proposal also called for air-bearing to allow the pod to levitate during transit. In order to supply the air bearings with pressurised air and further reduce drag, a compressor would suck air in through an inlet at the front of the pod. A linear motor system would be used to accelerate and decelerate the pod at high speeds while limiting the acceleration to 1g for passenger comfort.

## 1.1. Hyperloop Competition

Although the Hyperloop Alpha proposal was turned down, SpaceX decided in 2015 to hold a student competition[2] in order to drive the development of Hyperloop technology. To this end they constructed a 1,25km test tube designed to reaching an ambient pressure of 8mBar. The tube features an aluminium sub-track and rail mounted on a concrete fill bed.

Add picture of the tube

Since the first competition there have been a second and third iteration and a forth has been announced for the summer of 2019.

The objective for the teams is to build a prototype Hyperloop pod and race it in the the test tube. The pod reaching the highest velocity with successful deceleration wins the competition. During the first and second competition, a pusher vehicle was available to accelerate the pods to a pre-defined velocity at the beginning of their run. Therefore, it was optional for a pod to incorporate a propulsion system. However, in the third competition the pods were required to accelerate independently.

The first step of the competition is the Preliminary Design Briefing in which the team must outline the main concepts of their pod design. After it has been approved teams may proceed to submit the Final Design Briefing a few months later. This must include all details of the pod's design and show that the design is safe. Approximately 20 teams are then selected to compete in the competition at SpaceX headquarters in Los Angeles.

The competition in Los Angeles consists mostly of testing week where the pod must pass a series of tests to prove safety and correct operation before being allowed to enter the test tube. The most promising teams are then selected to compete in the final on the last day of the competition. Here teams aim to reach the highest speed and win the competition.

## 1.2. Swissloop

Swissloop was founded as an association in September 2016 by a group of ETH Zurich students with the intention of competing in the second iteration of the Hyperloop Pod Competition. Swissloop was able to gain support from many industry sponsors and several departments at ETH Zurich including the Integrated Systems Laboratory. In July 2017 Swissloop revealed it's first pod Escher to the public. After reaching the finals of the competition with Escher in August 2017, a new team was assembled to compete in the third competition in July 2018 with a completely new pod called Mujinga.

### 1.2.1. Escher

Swissloop's first pod design featured a cold gas propulsion system which was designed as for second acceleration stage after the initial acceleration delivered by the pusher. The pod also featured hydraulic bakes as well as a passive levitation system.

The avionics implemented for Escher included around 30 sensors and provided a reliable basis for controlling the pod. Although eventually several flaws became apparent, the system provided a solid basis for the development of the avionics system of Mujinga. While Mujinga retained some components of the hardware, the design ended up being completely different in several ways. The Software was almost entirely rewritten from the ground up leading to large performance and reliability improvements.

Add picture of Escher

### 1.2.2. Mujinga

Swissloop's second pod design builds on all the lessons learned with Escher and therefore consists of many drastic changes. Most noticeable, Mujinga no longer levitates but uses wheels and four electric motors as a propulsion system. Two high-voltage (700V) batteries produce 500kW of power to accelerate to a top-speed of 500km/h. Similar but redesigned hydraulic brakes decelerate the pod before the end of the 1,25km test track. A pneumatic clamping system presses the pod against the track to produce the down-force necessary to achieve the necessary acceleration.

As mentioned, the avionics system was based on the platform used in Escher. However, a large emphasis was placed on greater simplicity and reducing bottlenecks. A sever problem with the system in Escher was that the amount of data that could be logged was very small. Therefore, the logging system in Mujinga was specifically designed to handle much higher data rates.

Add picture of Mujinga

## 1.3. Project Scope

The scope of this Bachelor Thesis is the implementation of the avionics and control software running on the Hyperloop pod. This includes the following tasks:

- Platform selection
- Development of drivers to interface and communicate with on-board sensors
- Development of drivers for a network interface and SD card
- Development of drivers for communication with motor controllers (inverters), battery management systems and brake actuators
- Implementation of a control scheme which insures safe and correct operation of the pod while executing traction control and yaw control algorithms (developed by other people)
- Implementing communication with a control panel (developed by someone else) over a network and logging all collected data, as well as system events

The following tasks are not part of this bachelor thesis and were completed by other people:

- Design of custom PCBs (Hanno Kappen)
- Development of traction control(Julius Wanner and Stefan Weber) and yaw control algorithms (Yannick Strümpler)

- Development of a control panel for visualizing telemetry and controlling the pod (Laurin Paech)
- Wireless network for communication with the pod

# Chapter 2

# Specification

Diagram with all sensors etc.

## 2.1. Sensors

### 2.1.1. Laser Distance Sensors

In total four laser distance sensors were used to assess the vehicle attitude in relation to the rail.

Two high precision sensors were employed to measure the lateral alignment to the track at the front and the back of the pod. These sensors provided the input for the yaw controller in order to actively ensure that the pod is correctly aligned with the track and not exercising an torque on the rail.

Two smaller form-factor sensors were also installed at the front and back of the pod to measure the pods vertical alignment. These were mostly used to asses the performance of the clamping system.

### 2.1.2. Pressure Sensors

#### Ambient pressure sensors

A high-precision pressure sensor was installed to monitor the ambient pressure. Two further ambient pressure sensors were installed inside of each high-voltage battery pack, as these were pressurized. If the pressure inside the battery packs drops too low the battery cells could be permanently damage. Therefore, it was necessary to monitor these values and re-pressurize the pod's environment in the event of a leak.

#### Braking pressure sensors

Four high-pressure sensors were installed in the braking system. One in each braking piston to measure the pressure with which the brakes actuate and to determine their status. Additionally, one sensor was installed in each reservoir holding the pressure used to engage the brakes in order to monitor brake health. The braking system consisted of two independent hydraulic systems for redundancy, thus two sets of sensors were necessary.

### 2.1.3. Navigational Sensors

Two laser contrast sensors were used to detect optical marking on the wall of the test tube. The optical markings occur in intervals of 30m and can therefore be used to determine the location of the pod along the tube and calculate it's velocity.

## 2.2. Propulsion system

Four two-phase electric motors are used to accelerate the pod. Each is driven by a separate inverter. The inverters are controlled via a CAN bus and two digital safety signals. The RFE signal enables the inverter and the RUN signal connects the high voltage from the battery to the motor. The inverter can be configured over the CAN bus. Subsequently, both torque and speed commands can be given to the inverters to drive the motors. Furthermore, the inverters provide telemetry over CAN including the following:

- Inverter status
- DC bus voltage
- DC current
- Motor RPMs
- Motor RMS current
- Inverter temperature
- Motor temperature

## 2.3. Battery Management System (BMS)

Two battery management modules (one in each battery pack) are responsible for balancing the battery cells and monitoring them. These modules are also connected to a CAN bus and provide the following telemetry over it:

- High-voltage isolation status
- Battery Pack Voltage
- Discharge/Charge current
- Lowest cell voltage
- Highest cell temperature

## 2.4. Telemetry and Control Panel

To monitor the pod a network is made available inside the tube. The pod connects to this network and must transmit all telemetry necessary to assess the pod's state and make sure it is safe. In addition, the pod is controlled over the network. Should the connection to the pod fail at any point, the pod must enter a safe state immediately. To control the pod and display telemetry a control panel application was developed.

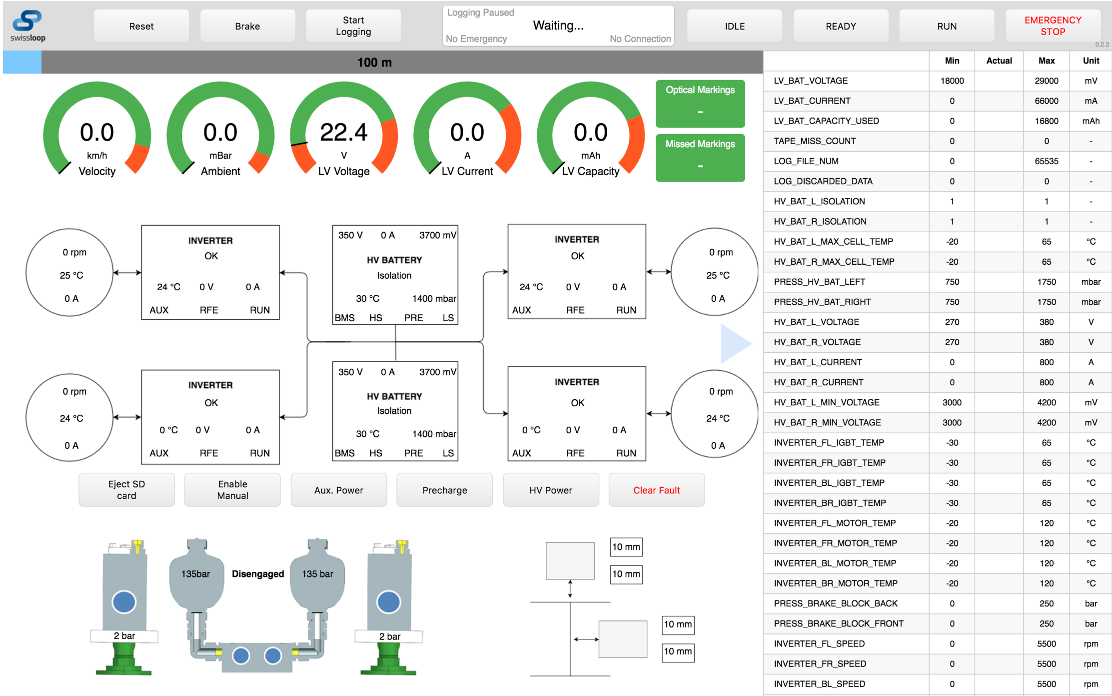


Figure 2.1.: Screen shot of the control panel.

## 2.5. Data Logging

In order to verify the pod's performance and diagnose possible failures, we wanted to be able to log as much data as possible. Therefore, we set a goal to log all sensor data that comes into the system.

Maybe add screenshot of plotting software?

## 2.6. Control and State Machine

Overall, the pod is controlled by a finite state machine (FSM). The FSM must incorporate all critical safety checks and is also used to allow the pod to complete the run autonomously. In order to improve testability, the FSM should have the minimum number of states necessary for the desired functionality. To this end we also decided to minimize the number of automatic state transitions, minimizing the risk of bugs in the implementation.

## 2.7. Correctness and Testability

The highest priority for this system was to ensure correctness and safety. Therefore it was important to minimize sources of errors and implement the system with testability in mind. Tests include unit tests for individual control sequences and algorithms, as well as functional tests.

Chapter 3

# Platform

The hardware platform used for this project is a combination of a custom designed PCB and a Texas Instruments Launchpad (LAUNCHXL-F28379D) featuring the TMS320F28379D micro-controller. The Launchpad provides a sold basis which includes all the components necessary to run the micro-controller. It then plugs into the custom PCB which accommodates all the necessary external components and incorporates connectors for all sensors and actuators.

References to MCU/Launchpad

Picture(s) of PCB + Launchpad

## 3.1. Micro-controller

The Texas Instruments TMS320F28379D was chosen as it provides high performance in terms of processing with two CPU cores and two Control Law Accelerators. In addition, it incorporates a wide range of versatile peripherals covering most types of interfaces used in the system. Furthermore, this processor is a dual-core version of the single core TMS320F28377S which proved to work very well in Escher.

## 3.2. Ethernet Controller

To establish a network connection on the test track an Ethernet connection was required. Since the micro-controller is not equipped with an Ethernet interface it needed to be included externally.

After considering several options we decided on the WIZnet W5500 Ethernet Controller. Beyond providing Ethernet support it also incorporates hardware implementations of ICMP, ARP, IPv4, TCP, UDP and other protocols. This is advantageous as it offloads the computation necessary to run the network stack from the main processor, providing better performance. Furthermore, the chip is widely used and therefore has good community support.

The micro-controller communicates with the Ethernet Controller over SPI but the W5500 also provides an interrupt line which can be configured to provide interrupts on events such as incoming packages.

## 3.3. SD-Card

In order to log telemetry data a form of non-volatile memory was needed. The data must be easily accessible and quickly retrievable. The obvious and most suitable choice is an SD-card, as it can be integrated into the SPI bus and provides large amounts of storage. At the same time it can be easily plugged into a laptop in order to retrieve the data in the field.

## 3.4. External Analog-To-Digital Converter (ADC)

The pressure sensors on the pod produce analog signals that need to be converted. Additionally, the pod incorporates a set of low-voltage batteries and it is necessary to monitor their voltage and the current consumption from them. Although the micro-controller features a built-in 12-bit ADC which could accomplish this task, we wanted to achieve higher precision using an external 24-bit ADC (ADS124S08). Communication with the ADC also runs over an SPI bus. However, the external ADC uses a different SPI mode than the Ethernet Controller and SD-card. Thus a separate SPI bus is required.

## 3.5. RS485 Bus

An objective in the design of this system, was to use as many digital sensors as possible. This was possible for both types of laser distance sensors used on the pod. Both support the RS485 serial bus. Using an appropriate RS485 transceiver, the Serial Communication Interface (SCI) of the micro-controller can be utilized almost natively to communicate with multiple sensors on a single RS485 bus. Unfortunately the two types of sensors use different bus settings and thus it was simpler to separate them into two buses with two sensors each.

Using the RS485 bus standard means less analog signals that are more prone to interference. It also allows for higher precision, as there are no precision losses during to conversions.

## 3.6. CAN Bus

The motor-controllers (inverters) used on the pod are designed for automotive applications, while the Battery Management Systems (BMS) are designed for aerospace applications. Therefore, both systems are designed to use the CAN bus for control and telemetry. The micro-controller incorporates a CAN bus and transceiver on the Launchpad makes communication with these devices possible without any additional hardware.

The main advantages of the CAN bus in this application are built-in bus arbitration and automatic retransmission. This allows devices on the CAN bus to transmit telemetry data asynchronously without the possibility of data loss.

Chapter 4

# Implementation

## 4.1. Structure

Division between CPU1, CPU2 and CLA. Main-loop structure. Data-flow. Static memory allocation.

## 4.2. Networking

Driver implementation using DMA. UDP. Telemetry and control frame structure. Cross-core communication.

## 4.3. Logging

Driver implementation. Use of FAT filesystem and trade-off with other file systems. Memory/Speed trade-off for SD cards. Event-based logging. Cross-core communication.

## 4.4. External Analog-To-Digital Converter (ADC)

Driver implementation and optimization.

## 4.5. RS485 Bus

General RS485 structure with SCI and transceiver. FIFO usage. RTS solution.

### 4.5.1. OADM

### 4.5.2. OM70

### 4.5.3. CAN Bus

General CAN structure. CAN driver from TI.

### 4.5.4. Inverters

Structure. State machine.

### 4.5.5. BMS

Structure. Event-based data.

## 4.6. Navigation algorithm

## 4.7. State Diagram

## 4.8. Control Law Accelerator (CLA)

## 4.9. Debugging

Smaller footprint printf library. Cross-core communication for printing

## 4.10. Unit Testing

Chapter 5

# Result

## 5.1. Competition

## 5.2. Conclusion

## 5.3. Outlook

Appendix A

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# Bibliography


[1] S. Elon Musk, “Hyperloop alpha,” 2013, [accessed 22-August-2018]. [Online]. Available: https://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf

[2] “Hyperloop pod competition,” [accessed 22-August-2018]. [Online]. Available: https://www.spacex.com/hyperloop

[3] D. E. Knuth, *The TeXbook*. Addison-Wesley, 1984.

[4] H. Kaeslin, *Digital Integrated Circuit Design: From VLSI Architectures to CMOS Fabrication*. Cambridge University Press, Apr. 2008.

[5] D. Hankerson, S. Vanstone, and A. Menezes, *Guide to Elliptic Curve Cryptography*, ser. Springer Professional Computing. Springer, 2004.

[6] NIST, *Advanced Encryption Standard (AES) (FIPS PUB 197)*, National Institute of Standards and Technology, Nov. 2001.

[7] P. Rogaway, M. Bellare, J. Black, and T. Krovetz, “OCB: A Block-Cipher Mode of Operation for Efficient Authenticated Encryption,” in *ACM Conference on Computer and Communications Security*, 2001, pp. 196–205.

[8] Xilinx. (2011, Nov.) Virtex-6 FPGA Configuration - User Guide. UG360 (v3.4) November 18, 2011. [Online]. Available: http://www.xilinx.com/support/documentation/user_guides/ug360.pdf

[9] ——. (2011, Oct.) 7 Series FPGAs Configuration - User Guide. UG470 (v1.2) October 26, 2011. [Online]. Available: http://www.xilinx.com/support/documentation/user_guides/ug470_7Series_Config.pdf