
DEPARTMENT OF INFORMATION TECHNOLOGY AND
ELECTRICAL ENGINEERING

Spring Semester 2018

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

Bachelor Project



Carl Friess
cfriess@student.ethz.ch

25 August 2018

Supervisors: Dr. Michele Magno, michele.magno@iis.ee.ethz.ch

Professor: Prof. Dr. Luca Benini, lbenini@iis.ethz.ch

Acknowledgements

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Abstract

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Nam dui ligula, fringilla a, euismod sodales, sollicitudin vel, wisi. Morbi auctor lorem non justo. Nam lacus libero, pretium at, lobortis vitae, ultricies et, tellus. Donec aliquet, tortor sed accumsan bibendum, erat ligula aliquet magna, vitae ornare odio metus a mi. Morbi ac orci et nisl hendrerit mollis. Suspendisse ut massa. Cras nec ante. Pellentesque a nulla. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Aliquam tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.

Declaration of Originality

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor. For a detailed version of the declaration of originality, please refer to Appendix A

Carl Friess,
Zurich, 25 August 2018

Contents

List of Acronyms	viii
1. Introduction	1
1.1. Hyperloop Competition	1
1.2. Swissloop	2
1.2.1. Escher	2
1.2.2. Mujinga	3
1.3. Project Scope	3
2. Specification	5
2.1. Sensors	5
2.1.1. Laser Distance Sensors	5
2.1.2. Pressure Sensors	5
2.1.3. Navigational Sensors	6
2.2. Propulsion system	6
2.3. Battery Management System (BMS)	7
2.4. Telemetry and Control Panel	7
2.5. Data Logging	8
3. Platform	9
4. Implementation	10
5. Result	11
5.1. Competition	11
5.2. Conclusion	11
5.3. Outlook	11
A. Declaration of Originality	12
Glossary	14

List of Figures

2.1. Screen shot of the control panel.	8
--	---

List of Tables

List of Acronyms

AES	Advanced Encryption Standard
ASIC	Application-Specific Integrated Circuit
DES	Data Encryption Standard
DVI	Device Independent File Format
ECC	Elliptic Curve Cryptography
ECDSA	Elliptic Curve Digital Signature Algorithm
EPS	Encapsulated PostScript
FPGA	Field Programmable Gate Array
IC	Integrated Circuit
IIS	Integrated Systems Laboratory
LED	Light-Emitting Diode
NIST	National Institute of Standards and Technology
PDF	Portable Document Format
WYSIWYG	What You See Is What You Get

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 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.

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

Add picture of the tube

1. Introduction

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. Introduction

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 severe 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 Strümpfer)

1. Introduction

- 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

2. Specification

battery cells could be permanently damaged. 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 its 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. Specification

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.

2. Specification

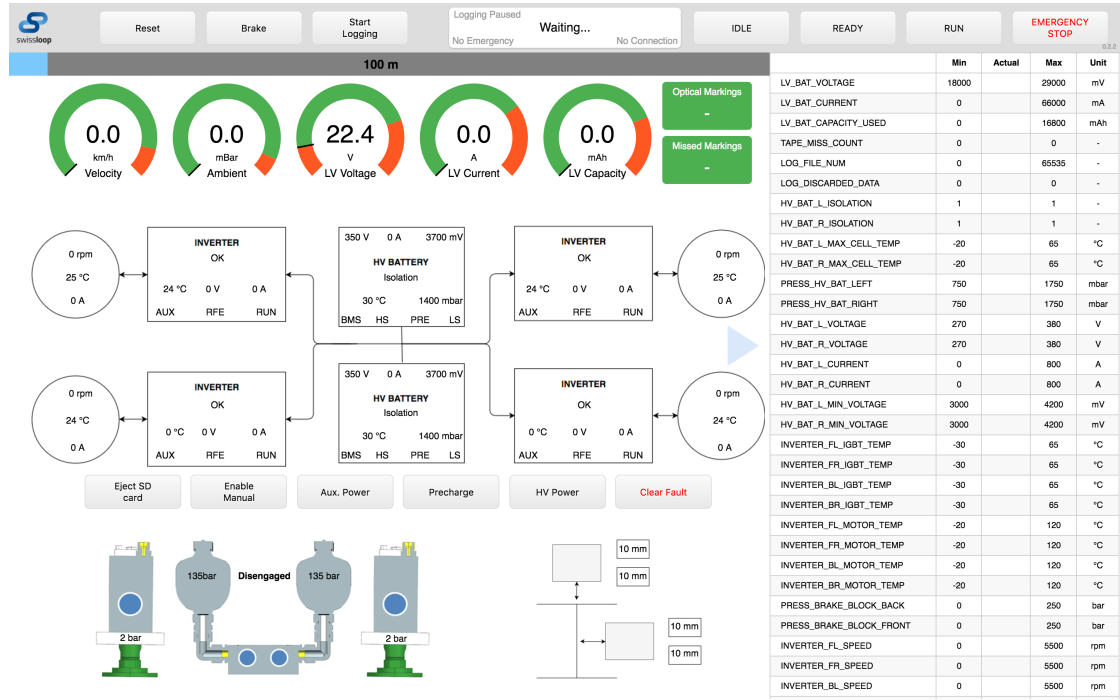


Figure 2.1.: Screen shot of the control panel.

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.

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.

Maybe
add
screenshot
of plotting
software?

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

- Present Platform - Present Sensors and other devices/systems

Chapter 4

Implementation

- Structure of system (E.g. What on CPU1 and CPU2?) - Flowchart?

Chapter 5

Result

5.1. Competition

5.2. Conclusion

5.3. Outlook

Appendix A

Declaration of Originality

Include the declaration of authorship with the `\includepdf` command (sign it and scan it). For more information about plagiarism, please visit <https://www.ethz.ch/students/en/studies/performance-assessments/plagiarism.html>

- **English version:** <https://www.ethz.ch/content/dam/ethz/main/education/rechtliches-abschluesse/leistungskontrollen/declaration-originality.pdf>
- **German version:** <https://www.ethz.ch/content/dam/ethz/main/education/rechtliches-abschluesse/leistungskontrollen/plagiat-eigenstaendigkeitserklaerung.pdf>



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

This is a sample title

Authored by (in block letters):

For papers written by groups the names of all authors are required.

Name(s):

First
Second

First name(s):

Student
Student

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date

Zurich, 01.01.2000

Signature(s)

First Student Signature
Second Student Signature

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Glossary

Apple Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.

Candle Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.

Guitar Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.

Monkey Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.

Snake Lorem ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua. At vero eos et accusam et justo duo dolores et ea rebum. Stet clita kasd gubergren, no sea takimata sanctus est Lorem ipsum dolor sit amet.

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