Development of Reliability Test Rigs for Total Artificial Heart Pumps

MARTIN OGEBORG
ALISA BESIC
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Utveckling av Reliabilitets-Testanordningar för Totalt Artificiella Hjärt-pumpar

ALISA BESIC
MARTIN OGEBORG

Examensarbete inom Medicinsk teknik och Elektroteknik
Grundnivå, 15 HP
Handledare på KTH: Fernando Seoane
Examinator: Mats Nilsson

Skolan för Teknik och Hälsa
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Kungliga Tekniska Högskolan
Skolan för kemi, bioteknologi och hälsa
141 52 Huddinge
https://www.kth.se/
Abstract

The long-term performance of TAH pumps needs to be demonstrated. Reliability tests are performed to measure its ability to operate for months, or years, without failure. Real Heart is currently constructing test rigs for this purpose. Software for documenting test rig conditions is also required. Thus, the objective of this study is to assist in developing reliability test rig software.

The software is written in LabVIEW and is hosted on a CompactRIO controller. Requirements include sampling of sensor data, logging, and alarms. Additionally, a PC dashboard is constructed for monitoring real-time data, reviewing logs, as well as controls for acquisition.

Results of this study present a foundation for the test rig software. It features a modular architecture which allows for future scalability. The process of development involves research of hardware/software, establishing a reference design and to build and validate each module through test simulations. Data acquisition is set up with the NI-DAQmx API. It features automatic configuration for thermocouple, as well as custom signal scaling of the pressure and flow transducers. However, grouping of data and synchronization for logging and alarms was a challenge. The producer/consumer design pattern is implemented for grouping data as well as synchronization for logging and alarms.
Sammanfattning


Acknowledgement

This project was performed during the spring of 2022 in the academical fields of electrical and medical engineering. To understand the content of this report the reader is recommended to possess basic knowledge of medical terminology associated to the human heart.

We would like to thank the company, Scandinavian Real Heart AB, for letting us be a part of this project. And a special thanks to our supervisor at the company, Soteris Andreou, for all the help and support he provided for our work.

We would also like to thank our supervisor at KTH, Royal Institute of Technology, Fernando Seoane, in addition, Heikki Teriö, for helping us gather all the ISO documentation that were required for this project.
### Glossary and Acronyms

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<th>Definition</th>
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<tr>
<td>TAH:</td>
<td>Total artificial heart</td>
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<td>MCS:</td>
<td>Mechanical Circulatory Support</td>
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<tr>
<td>FDA:</td>
<td>U.S. Food and Drug Administration</td>
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<td>MDR:</td>
<td>Medical Device Regulation</td>
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<td>ISO:</td>
<td>International Organization for Standardization</td>
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<td>IEC:</td>
<td>International Electrotechnical Commission</td>
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<td>EIC:</td>
<td>European Innovation Council</td>
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<tr>
<td>Ni:</td>
<td>National Instruments; a company producing and providing technical components and systems</td>
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<tr>
<td>cRIO:</td>
<td>CompactRIO; an embedded system for reconfigurable I/O modules</td>
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<td>RTOS:</td>
<td>Real-time operating system, manages tasks of the embedded software</td>
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<td>FPGA:</td>
<td>Field Programmable Gate Array</td>
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<td>ADC:</td>
<td>Analog to Digital Converter</td>
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<td>FIFO:</td>
<td>First in; first out</td>
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<td>VI:</td>
<td>Virtual Instrument; a set of functions, or processes, in LabVIEW</td>
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<td>Mock Loop:</td>
<td>In-vitro test rig, used for simulating natural human conditions</td>
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Appendix A. Flow chart
Appendix B. Results from annual report of 2021 (in Swedish)
1 Introduction

1.1 Problem definition

In today's healthcare regarding transplantation of the human heart, the supply of available hearts has difficulties meeting the rising demand. The heart is a vital organ that is not readily available and the waiting times on the transplant lists are on average six months for an adult. However, this can vary, and it can take even longer depending on blood type, disease, and compatibility. A total artificial heart (TAH), Realheart TAH, is currently under development by the company Scandinavian Real Heart AB. The Realheart TAH is designed to mimic the functions of a natural human heart. It is meant to function as a substitute when patients wait for a new heart, and there are future aspirations that the product can be placed in a human for longer periods of time [1].

Deeper studies need to be done to investigate the Realheart TAH's impact on the human cardiovascular system, and to further improve its mechanics. Artificial hearts and other implantable medical devices have some defined requirements about its technical specifications, functionality, and performance for it to be reliable and safe for implementation. These requirements are regulated by the U.S. Food and Drug Administration (FDA) (in the United States), Medical Device Regulation (MDR) (in Europe) and dictated by International Organization for Standardization (ISO). Therefore, it's necessary during development to study and document the performance of the Realheart TAH to fulfil these requirements [1].

1.2 Goals

The main goal of this project has been to help Scandinavian Real Heart AB with developing embedded software for a CompactRIO System Controller. The controller will be used to monitor multiple test rigs that are constructed for reliability testing the TAH-pumps. The software needs to handle sensor data acquisition, logging, and real-time monitoring of the test rigs. The parameters that will be monitored are temperature, pressure (pre- and afterload), and volumetric flow. Lastly, alarms will be implemented into the software to warn when problems occur with the test rigs.

The goals are specified as following:

- **Logging.** Two types of logging: Event logs (events such as pump failure, the rig was turned on/off, or alarms) and value logs (snapshot of values from the sensor over a certain amount of time).
- **Alarms.** The rig should monitor the sensor values and send out an alarm if there is any deviation from the permitted range. Notification via email or text.
- **Dashboard.** Shows the instantaneous values of each sensor, the state of the rig, and the last entries to the event log. Monitor Screen display. Add notes with timestamp and operator name. Tab to show historical data.
1.3 Delimitations

This thesis doesn’t consider any parameters other than those mentioned above: pressure, temperature, and flow. The Real Heart is responsible for the construction of the TAH pumps and the test rigs. There will be eight test rigs for this project, but our focus will be to implement the software on only four of them. The project includes ten weeks of full-time studies with three to five weeks of additional weeks if necessary. The work will also cover issues concerning ISO-standards and sustainability with a focus on the social and economic aspect and not the environment.

1.4 Tools and Components

Real Heart has provided us with products and components that we will work with. These have included:

- cRIO-9056, National Instruments CompactRIO Embedded System Controller.
- NI-9210, Thermocouple Analogue Input Module (Temperature Acquisition).
- NI-9237, Quarter/Half/Full Bridge Analogue Input Module (Pressure Acquisition).
- NI-9361, Counter Input Module (Volumetric Flow Acquisition).
- Cables.
- Pressure transducer.

The embedded application is developed in LabVIEW 2021 (32bit).
2 Background

2.1 Scandinavian Real Heart

Heart failure is today still one of the leading causes of death in the world. It is such a serious disease that more people die of cardiovascular disease and heart failure than all cancers combined every year. The waiting times on the transplant lists for a new heart amount to several months or more than a year and in some cases, it is far too late for the receiver to get it in time. In comparison to the need of a heart, the availability of donated hearts is limited. Since 2007, heart transplants have increased to approximately 60 per year in Sweden [1]. But it is still not enough and there is a need for something that can change this problem.

The company Scandinavian Real Heart was founded in 2007 by Azad Najar and two of his companions with the goal of creating and developing a heart pump that will mimic the functions of the human heart [2]. This heart pump is called Realheart TAH. The TAH should act as a substitute pending a heart transplant.

The development of the product has been going on for several years steadily and according to schedule. The company is collaborating with world-leading heart surgeons, engineers, and researchers to drive this research towards its ultimate product [2].

The design of the basic idea and the updated construction (atrial function) for the artificial heart is patented in several countries, including Sweden, Germany, France, China, and the United Kingdom and is valid for 20 years. The design of the heart pump consists of two valves in an AV-plane between two chambers and two atria. So, the patent is on the idea/innovation with a four-chamber heart pump instead of a two-chamber heart pump that currently exists on the market and is the competing product. The function of the heart is also protected by the patent. The function is that the pump pumps blood by moving the AV-plane up/down between the chamber and the atrium [3].

There is also an ongoing application in India and the USA. Furthermore, they have also applied for patents in all countries mentioned above for: "Heart in Service Prosthesis", "Split Sternum Prosthesis", "Artery Coupling 1 & 2" and "Automatic Heart Control". All of these are components that belongs to the product as a whole. Even these are under patent pending [1]. And the latest news was that a patent in USA was approved in December 2021 for the idea and construction of a concept containing four chambers and two pumps until year 2035 [4].

The patent thus means that the design, in addition to chambers, has atria and self-designed connections between them, which means that TAH should and will mimic the functions of the human heart for a better and safer lifespan and quality [1].

TAH can be used as a temporary treatment while waiting for a transplant or as a permanent therapy for those patients who, for various reasons, are not candidates for transplantation.
2.2 Financial aspect

Since Realheart does not yet have a finished product launched, the company has no revenue mechanisms in place that generates any sells nor offers any services that produce any profit. Instead, the company has its focus on development and commercialization and all the revenue that the company shows is from financial support [4]. This means that a large part of the resources is invested in the development of TAH. This is because their studies and tests must be successful in order for the goal of a finished product to be achieved. If the preclinical and clinical tests have good positive results, then it leads to Realheart being funded. It is then easier to raise capital elsewhere than just by Swedish investors. It is also important that the company obtains important licenses and certificates for its product to be able to declare security and be approved on the market. If, on the other hand, the company does not receive these, and if the product and/or its development does not meet the standard, it leads to a negative impact on the business in the form of financial setbacks and earnings [1] [4].

In December of 2021, Realheart received confirmation that they will be listed on Nasdaq First North Growth Market under the share name HEART. This means that they can bring in even more and bigger investors to the company and it is very positive for the purpose of development and commercialization. The more investors, the more money comes into the business. Realheart currently has 33,183,461 shares on the market [3] [4]. In order for the company to continue to operate, they are in great need of their shareholders. This is because it does not have many other sources of income or long-term financing and will be dependent on capital injections to be able to run its development program [1].

As mentioned earlier, Realheart does not generate any income, which even then means that no dividend has been paid to shareholders either. It is a big risk shareholders take when investing, it can take time if or when a dividend will be made. So, for that to be possible to happen later in the future, it all depends on what the earnings trend, future cash flows, financial position, investment and working capital needs to look like for the company [5].

The 2021 annual report published by Realheart has shown that the rights issue carried out during the year now has a liquidity position with approximately SEK 42 million in cash and cash equivalents. Furthermore, the European Innovation Council (EIC) has also awarded a grant of SEK 25.7 million, which the company will have access to in 2022 and is expected to be consumable until Q2 2023. Furthermore, the company also needs to bring in more long-term financing needs and this is a problem Realheart is trying to evaluate other options for further capitalization. One of the solutions is to continue getting financing with equity from financially strong owners as well as from other sources such as EU support and non-profit foundations [4] [5].

The company’s numbers over the past year are displayed last in this report (In Swedish).
2.3 Standardizations and regulations

All companies in some type of the medical field regarding marketing, development, manufacturing, export and more, must require licences and certifications and follow standards and regulations provided by special governing authorities [3]. These are: ISO, MDR (in Europe), International Electrotechnical Commission (IEC) and even FDA if the product is launching in the states. The definition of these standards is that they set minimum requirements regarding trust, reliability, safety, and efficiency [6].

ISO and IEC are international non-governmental and independent organizations. It is a partnership between many countries. ISO says: “Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges.” [7].

IEC says: “They provide instructions, guidelines, rules or definitions that are then used to design, manufacture, install, test & certify, maintain and repair electrical and electronic devices and systems.” [6].

IEC standards are very important regarding quality and risk management. It's necessary that researchers understand the importance of innovation so that manufacturers can consistently deliver high-quality products and good performance. Those who use IEC International Standards are technical experts. Another usage of the international standards is that they are the basis for testing and certification [6].

The organization's standards are the most important since ISO and IEC are the biggest providers for these regulations and all companies must follow the necessary ones even if it is not required by the country’s own laws. This, because partners might require it and for the company to be able to launch the product in the desired countries.

The Real Heart and their partners are using a couple of the standards and regulations from ISO, MDR and IEC since they have patents on components for the mechanical heart in a few European countries and the US. Some of them are:

- ISO 13485:2016 Medical devices – quality management systems – requirements for regulatory purposes
- ISO 14971:2019 Medical devices – application of risk management to medical devices
- IEC 62304 Medical device software – software life cycle processes
- EN 60601-1 Medical electrical equipment - Part 1: General requirements for basic safety and essential performance
2.4 The basics of a human heart

The heart is the second largest and one of the most important organs in a human. It is a muscle with various important functions and is difficult to replace if its functionality is not optimal since a heart is unusual to come by. The myocardium (the heart as a whole) works in such a way that it drives blood through the entire body's circulatory system and keeps it running. The heart construction consists of two atria and two chambers with one of each on the right and left side of the heart, as well as valves. The right ventricle drives oxygen-poor blood through veins to the lungs via the pulmonary artery and the left ventricle directs oxygen-rich blood through arteries to the remaining parts of the body via the aorta [8].

The blood passes the heart from the right to the left side through pressure that occurs. The blood is squeezed through the heart with the help of two types of valves. These are one-way so the blood cannot flow back. Between the atria and chambers there are atrioventricular valves and between the chambers and the pulmonary artery and aorta, there are aortic valve and a pulmonary valve. The mitral valves consist of flat strong connective tissue flaps that attach to the tight connective tissue ring that exists between the atrial and ventricular parts of the heart. When the heart chambers receive blood from the atria, the valve seal opens and provides resistance to the blood stream. As the chambers further contract, the mitral valves are pressed against each other and are tightened together by the thin tendon threads as the papillary muscles contract. This prevents the mitral valves from opening back up in the atria when the pressure in the chambers rises [8].

The aortic valves are the ones that are located between the left ventricle and the aorta as well as the right ventricle and pulmonary artery. The aortic valves are attached to the artery wall and when blood flows out into the artery, the thin connective tissue valves are pressed out against the blood vessel wall, and blood is allowed to pass. When the pressure in the chamber drops, the pockets are filled with blood, and the aortic valves are contracted, thereby closing the blood vessel off. This prevents the return of blood to the chamber [8].

2.4.1 Cardiac conduction system

The conduction system of the heart consists of special muscle fibers, which generate and conduct electrical impulses. These electrical impulses emanate from the sinus node, which is placed in the right atrium which the upper cavity vein directs the blood to. From the sinus node, the electrical signals spreads through the atria, stimulating them to contraction. The impulses are collected in a special muscle node on the border between the atria and the ventricle, called the atrioventricular node. This one lead electrical impulses slowly and it takes 0.1–0.2 seconds for the impulse to spread further through the chambers' conduction system. This small time-delay allows blood to flow from the heart's atria to the chambers before they contract. The continued impulse spread takes place via His' bundle, which divides into two parts, one for each chamber. Through rapid impulse spreads in the chamber's conduction system, the heart muscle cells are activated, producing a sharp heart muscle contraction, that is, a heartbeat [8].

FIGURE 1: Anatomy of the heart
2.5 Realheart - Total Artificial Heart

The design of this medical device has been developed for several years and what distinguishes this product from other competitors in the market, is that it has a four-chamber design. A four-chamber construction means that the machine provides a natural pulse and blood flow with both chambers and atria with associated valves in addition [1]. According to studies, this has been shown to give fewer side effects than the competing technology available on the market today, where the designs only consist of chambers.

The TAH is controlled by a control unit and a battery belt together with a thin driveline connected between the TAH and the components outside the body. It is desired that the patient can have as high freedom of movement as possible, therefore the design is of utmost importance. For the patient to have a comfortable quality of life, even though there is a driveline outside the body, the component has been made of flexible, soft, and biocompatible material. With these characteristics, the driveline should not get in the way of natural everyday movements, which reduces the patient's discomfort [9].

The method chosen was a battery system that is electrically powered. This is to make it more user-friendly, with reduced noise and increased comfort for patients. Furthermore, what distinguishes this product from the others (as previously mentioned) is that the construction also has atria. This means that in practice, there will be a more synchronized pump flow of the blood and better balance on both the left and right sides of the heart with the help of the atrial pump pressure function/contraction.

The pumps are designed in two separable units for easier individualized placement and thus safer connection to the body's vessels via self-designed couplings made of biocompatible materials for reduced risk of infection [1] [9].

FIGURE 2: TAH placement
2.6 Reliability testing of mechanical circulatory support devices

All mechanical circulatory support devices (MCS) are required to undergo reliability testing before being put into clinical trial. ISO defines reliability as "probability that an item can perform a required function under given conditions for a given time interval \((t_1, t_2)\) for a specified confidence level." [10]. The National Clinical Trial Initiative Subcommittee has stated reliability recommendations for long-term MCS devices [11]. Long-term is defined as 30 days or more, but typically amounts to months or years for MCS devices. The testing method should be modelled by the strengths and weaknesses of the devices. In-vitro tests are then carried out in a simulated setting, represented by a mock loop, with relevant loads parameters applied.

Multiple reliability studies have been conducted for MCS devices under pulsatile load. A long-term reliability test was performed on the EVAHEART LVAD by T. Kitano et al. [12] to demonstrate its durability for two years operation under physiological and pulsatile load. Eighteen pumps were initially set up in a mock loop and operated for an average of 777 (max, 817; min, 741) days without failure, and six of the pumps continued operating for an average of 8.6 years (max, 9.0 years; min, 7.6 years). Pump performance had no significant change, and its reliability was evaluated to 90% with an 88% confidence level.

Other reliability studies have monitored the effects on, inter alia, pre- and afterload. The SynCardia TAH was studied by Crosby et al. [13] to evaluate different load parameters during a simulated heart failure. The study indicated the TAH's sensitivity in afterload while running with reduced output. Another study conducted on the Reinhart TAH 2.0, by S. Hildebrand et al. [14] investigated the sensitivity on pre- and afterload when controlling the heart rate and the diastole of the right side. The test revealed successful controllability in the pressure range of 60 - 140 mmHg, which was the testing range.

Many variants of mock loops have been used to simulate physiological conditions for in-vitro studies. Furthermore, a numerical model has been suggested by Gregor Ochsner et al. It's a hybrid mock loop consisting of an analogue electrical circuit running simultaneously with the mock loop. It is claimed to be superior to the conventional model [15].
3 Method

This report has been conducted as a literature study, in addition to practical work. The literature studies have focused on background by reviewing previous work about reliability testing and gathering knowledge of the current standards for medical devices. A lot of research has also been conducted to learn LabVIEW, and to study the hardware components. These studies have been crucial for the practical work which has revolved around developing software for reliability test rigs.

3.1 Hardware

This project has been provided a CompactRIO Controller by the Scandinavian Real Heart. CompactRIO is an embedded system that contains a real-time processor, a reconfigurable FPGA, and interchangeable industrial in- and output (I/O) modules, which connect to almost any sensor or actuator. Its long-term reliability is beneficial for the purpose of its later use.

The provided real-time controller (cRIO-9056) supports up to eight slots of, analogue or digital, I/O modules. Its chassis (as shown in fig. 3) will be equipped with: One thermocouple input module (NI-9210) for temperature measurements; two counter input modules (NI-9361) for volumetric flow acquisition; and two full-bridge input modules (NI-9237) designated for pressure acquisition.

1) NI-9210 – Thermocouple Module: Features four channels of analogue input, type k cords, 14 samples/sec.
2) NI-9361 – Counter Module: Features eight channels of digital inputs, 0 to 5 V, 32 bits ADC resolution and internal clock at 102.4 kHz.
3) NI-9237 – Pressure Module: Features four full bridge channels of analogue inputs, ±25 mV/V, 24 bits ADC resolution, 50k samples/sec/channel.
4) a) Thermocouple, type k: measures temperature from the wires.
   b) Blood pressure gauge.
   c) Pressure transducer: measures pressure, applied from the blood pressure gauge.

Please refer to the National Instruments website for a full specification overview of the C series I/O modules [17] [18] [19].

The current setup is supposed to monitor up to four test rigs, running simultaneously. Each test rig, therefore, needs one thermocouple channel, three channels for pressure sensors and two channels for flow sensors.

Due to practicalities, testing of hardware is not done directly on the test rigs. Therefore, a blood pressure gauge is used for simulating loads on the transducer to verify that the pressure acquisition works correctly.
3.2 Software

The embedded software is going to be programmed using LabVIEW and the LabVIEW Real-Time Module. LabVIEW is a graphical programming environment for developing advanced control systems. Both LabVIEW and CompactRIO are developed and maintained by National Instruments. Therefore, LabVIEW provides support and accessibility for the embedded system controller.

It is important to have a general idea of the software’s architecture prior to development. The requirements for the software (as declared in 1.2 Goals) have been thoughtfully split into individual tasks. Tasks are then grouped by function to form multiple processes that will run in parallel. A process is a loop which executes one or more tasks continuously.

The planned architecture is presented as a flowchart (in app. A). It demonstrates three top-level applications (blue containers), containing its respective processes (yellow blocks) and expected data flow (arrows).

The User Interface will be deployed on a lab PC running Windows. This application should contain all necessary dashboard features. It will run the following processes:

- **UI Event handler** – This task handles events generated by user inputs.
- **Command Sender** – This task creates commands to be sent over network.
- **UI Update** – This task updates the dashboard overlay with real-time data and log entries.

The real-time application processes will be managed by a real-time operating system (RTOS). It contains the following:

- **Data Acquisition and Analysis** – Is a collection of parallel tasks that samples data from the connected controller modules, creates data points for logging and checks the data for out-of-range values.
- **Logging Engine** - This task will calculate the mean average, organize, and log the data received from the Data Acquisition process, then save it to local storage on the controller.
- **Alarms** - This task will send an email containing info of any errors that are detected during execution.
- **Command Parser** – This task receives network sent commands.
- **Message Handler** – This task distributes commands received by the Command Parser.

The FPGA application handles raw data from the I/O modules. However, this isn't needed because LabVIEW provides automatic configuration of the FPGA and I/O modules with the help of NI-DAQmx. NI-DAQmx features data acquisition drivers, driver architecture and API including functions and development tools for NI DAQ devices.
4 Results

The resulting software, disregarding the FPGA application, corresponds to the initial software design. It features a real-time application hosted by the controller and a User Interface representing the PC dashboard.

The real-time application is structured from a top-level skeleton (as shown in fig. 4). LabVIEW uses block diagrams, including graphical icons and wires, to resemble data flow from left to right. Each icon, also known as “SubVIs” (Sub-Virtual Instrument), represents a smaller part of the code for the overall application. The block diagram holds SubVIs for start- and stop routines (RT Start/Stop), the parallel running processes (RT Network Reader/Alarm/Logging/Data Acq…), and error handling routines (Simple Error Handler).

The top-level skeleton is later meant to be assigned as the start-up application. That allows it to run continuously by deploying the software to the non-volatile memory of the CompactRIO.

The general idea of the software architecture was realized by using a combination of different design patterns. The two major design patterns that were used are called “Producer & Consumer” and “State Machine”.

Producer & Consumer is used to distinguish deterministic (producer) and non-deterministic (consumer) processes. Deterministic processes, in this case Data Acquisition and Analysis, have a time critical deadline to meet for each iteration. This deadline is time critical to prevent any loss of data from the reliability testing. This data is then passed on to the consumers, which is the Logging and Alarms, via queues to be processed in a slower rate. Queues are set up as a buffer that uses a FIFO methodology. Multiple queues have been set up to help distinguish the data flow.

Data acquisition was set up with the help of the NI-DAQmx API which is provided by the LabVIEW Real-Time Module. It features a hardware abstraction layer for configuring and reading the input modules, and more functionality. NI-DAQmx also allowed for the NI-9237 and NI-9361 to synchronize acquisition through hardware. This is done by having a master and slave configuration where the NI-9237 shares its time base with the NI-9361 (as shown in fig. 5).
FIGURE 5: Master (NI-9237) and slave (NI-9361) configuration used in the Data Acquisition process [16].
The NI-9210 proved to be a multiplexed-, slow sampled module. All its channels share the same ADC, and the sample rate is too slow for being hardware synchronized with the other modules. It has therefore been assigned an individual loop which reads all four channels simultaneously.

The State Machine design pattern is used within the Data Acquisition and Analysis process. The following states are used:

- **Stopped**: In this state data acquisition is still running. However, no data is passed on to the consumers. Real-time values are updated only to verify that the acquisition is working. Next state is Initial or Calibration if a start or calibrate command is received.

- **Calibration**: In this state the pressure sensors are calibrated. This is done by configuring the scaling of the raw input data and adding a zeroing component. This is done with the help of a function for zero-point calibration included in the DAQmx API. Next state is Stopped.

- **Initial**: In this state a timer with a period of 300 seconds, and three arrays to store temporary data are initialized. Next state is Running.

- **Running**: In this state the data acquired from the input modules is stored in the arrays. Next state is Enqueue if the time period meets its deadline or Stopped if a stop command has been received.

- **Enqueue**: In this state the data is passed on to the consumers, e.g., logging. This is done by enqueuing the acquired data. Next state is Initial.

### 4.1 Logging

The Logging process is a consumer of data, and only needs to execute when there’s data to be consumed. The data is acquired as a cluster, which is a type of array that can hold a variety of data types, from the Data Acquisition and Analysis process. The cluster holds all the values of the parameters (temperature, pressure, flow and current), a timestamp, and a string to distinguish which test rig the data belongs to. It then calculates the mean average of each parameter and organizes the data into a TDMS-file. The TDMS file extension is compatible with Microsoft Excel.

Event data is handled in a similar way in a parallel process. It receives a different cluster containing a string for which test rig it belongs to, string with a severity indication (warning, info, or error), and a string that contains a brief description of the event. These logs are then saved onto the hard drive of the CompactRIO.

### 4.2 Alarms

The Alarms process only execute when an alarm has been triggered. The process consumes a string containing information of what caused the trigger and where it comes from. It then puts together the string into an email and sends it to a specified recipient. Currently it only triggers for specified value ranges, minimum and maximum, that are implemented into the real-time application. These values are the mean average that is calculated from the data acquisition. This consists of temperature, pressure, and flow. The Alarms process still needs to be configured to trigger an alarm when software or hardware errors occurs. This is not mentioned as a goal, but the company insists for this to be implemented as a feature.
4.3 Command Parser and Message Handler

Command Parser and Message Handler were added last to the real-time application. These processes are contained in the RT Network Reader VI. Command Parser sets up a network stream that receives and unpacks commands that is sent by the dashboard. The network stream is set up as a connection to the dashboard and needs to be configured by a network administrator of the company. This process then enqueues the command to be consumed by the Message Handler. This then distributes the command for the real-time application.

4.4 Dashboard

The dashboard consists of three processes. The UI Update is used to display real-time values of temperature, pressure, and flow. This process reads what is called "network shared variables" which is a type of global variables that is hosted on the CompactRIO. These variables are directly accessible through a network connection. The Data Acquisition and Analysis process is responsible for updating (writing) these variables, and the UI Update only reads them. These variables are a lossy way to represent data but stable enough to give a sense of real-time data. The UI Event Handler react to all user triggered events, like pressing a button. This process then puts the specific command and enqueues it to be consumed by the Command Sender. It then connects to the CompactRIO through a network stream. Then it periodically scans the queue if there is any command to send further.
Our goals for the thesis have mostly been achieved. The goals were to develop a logging and a dashboard application, and alarms for when a problem with the data acquisition occurred. Further down this discussion, the goals of the thesis will be defined.

We have had a lot of weeks to work on this project, but some minor unforeseen problems with the development of the application have occurred. We have had access to prior work for a similar application, but it wasn’t helpful for our work. The application lacked scalability for running multiple test rigs, since it wasn’t configured for simultaneous data acquisition. Therefore, the application had to be rewritten from scratch in LabVIEW. This proved, for multiple reasons to be a bit of a challenge.

Having some experience with embedded systems, general programming and knowledge about digital electronics made this project possible. Furthermore, programming embedded software for the CompactRIO is easily done by the LabVIEW environment. Data acquisition is easy to set up through DAQmx for all modules, but the scale of the project presented some challenges regarding abstraction of the test rigs. Because the temperature module (NI-9210) is multiplexed, its main challenge was to synchronize data acquisition with the other modules. Also, this made it difficult to distinguish its channels for respective test rig. There exists another analogue voltage input module, NI-9215, that could do the same type of measurements and have the same benefits of simultaneous sampling like the other modules used in the project. The benefit with NI-9215 would be to easily collect all data input channels for respective test rig in the respective process, which we were unable to accomplish with the NI-9210.

Flow module (NI-9361) and the pressure module (NI-9237) were easy to set up in the same process, which helped a lot with the abstraction. They were also possible to synchronize by hardware, which made the data acquisition more precise and reliable. The company wants to use another flow meter than originally intended, the BioProTT. The flow meter can only output either analogue or digital signals, which is not supported by the NI-9361. However, this flow meter would preferably be connected to an analogue module for the CompactRIO’s chassis. This makes scaling of input data easy to set up because it scales linear with the output current of the flow meter. We would suggest the NI-9208 module which would be able to acquire current readings and convert it to volumetric flow. The digital interface would have the benefits of acquiring status messages and data simultaneously. That would however require to set up a separate process for parsing the digital messages and would make synchronization much more complicated to achieve.

Another way to program the modules would have been to directly program the FPGA target of the chassis. Even though NI-DAQmx offers simplicity and to quickly develop and deploy applications to the CompactRIO, it’s not as efficient as reconfiguring the FPGA directly. A lot of data processing could have been offloaded onto the hardware, which currently is done by software. This could save a lot of resources for other processes or contribute to system stability if that was of concern. Also, this would help a lot with the abstraction of the test rigs by bunching together each input data into respective test rig. Then you would transfer the data by setting up a FIFO transmission between the real-time controller and FPGA for respective rig. FPGA programming is not for any novice developer though and would require a lot more time, and understanding of the entire system, to configure correctly.

The timeline of the project presented another challenge because a lot of the time were consumed by learning LabVIEW and studying the embedded system, and all its components. Because the scale of the project was to implement the software to monitor four test rigs, it was of biggest importance to get the architecture done correct from the start. Therefore, a lot of time was spent learning the best practices of LabVIEW, and to learn which design patterns to follow during development. More time had been beneficial to perfect the embedded software, and to study if it’s stable enough for long-term operation.
One thing that's on our minds is if there exists any type of small memory leaks, or if the timing of all deterministic processes is sufficient. Only time will tell if the real-time application meets those requirements. However, if any timing errors or memory problems show up later, it will be easy to diagnose.

Making corrections could then potentially bring up unforeseen issues that never were considered from the beginning of the project. That is the biggest reason why the architecture had to be done right from the start.

Dashboard, data/event logging and alarms presented no further challenges and were easy to program from the start. These applications are still missing some minor details for them to be implemented into the completed software. For the dashboard, it will show real-time data parameters, but all its inputs and outputs need to be connected to the command sender/message handler. Also, the design of the dashboard needs to be structured further to make it more user friendly. This needs further work, but this hasn’t been of priority during the project and won’t be finished until deadline. We predict this needs at least another week to be configured correctly into the software. For the alarms, the application can alarm through emailing a specified recipient but the triggers that will generate an alarm need to be implemented. The triggers for value ranges, error messages and other warnings need to be set up into the core of the program. This requires more research on how to synchronize with the rest of the application. Depending on the difficulty of the synchronization this might take another two weeks of work.
6 Conclusion

To sum up this thesis, it has been interesting working with a company, and it was very rewarding seen to that it has been a positively and complex challenge to accomplish. LabVIEW is rather easy to learn for novice developers. Graphical programming provides a full-scale overview of the system which is useful for students learning embedded programming. LabVIEW is also compatible with other types of controllers and languages making it easy to work with.

The project has been provided with useful products and information. Working close with LabVIEW and CompactRIO and its components has been a pleasure as well as educational. The results provide a great foundation for the test rig software, that are helpful and rewarding for both the company and the readers.

Future work, as mentioned in chapter five, would need to focus on further improving synchronization of data acquisition, implement proper alarm triggers and create an organized and user-friendly dashboard. The state of the current application features a great foundation for the company, or other students, to achieve the goals in just a couple of weeks.
7 References


Appendix A: Flow chart
Appendix B: Results from annual report of 2021 (in Swedish).

### Balansräkning i sammandrag

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