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DEVELOPMENT OF A FORCE SENSOR FOR IOTSPORTS: THE BOAT ROWING APPLICATION

Master's Thesis

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JÕUANDURI ARENDUS ASJADE INTERNETI SPORDIRAKENDUSTESSE: SÕUDMISAERU JÄLGIMINE

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Author’s Declaration of Originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The Internet of Things is a major driver for new innovations in the electronics industry. Its applications cut across almost every aspect of human endeavour. With this increase in applications, comes the added challenge of finding new sensor solutions to meet peculiar demands of users. The sensor data increases in volume as a result but the new information obtained is helping make lives better and easier. A good example exists in the field of sports where athletes, coaches and enterprises are requiring more and more sensor information to monitor, assess, and improve performance. This work covered the design, development and implementation aspects of an IoT product development in the field of sports.

This thesis is written in English and is 66 pages long, including 5 chapters, 37 figures and 6 tables.

Annotatsioon

Jõuanduri arendus asjade interneti spordirakendustesse: sõudmisaeru jälgimine

Asjade internet on oluline elektroonikatööstuse innovatsiooni vedav jõud. Selle rakendused on seotud juba peaaegu iga inimtegevuse aspektiga. Seoses rakendusvõimaluste kasvuga lisandub uusi väljakutseid sobivate andurite leidmiseks, mis rahuldaksid kasutajate spetsiifilisi vajadusi. Sensorandmete hulk kasvab mahult, aga uus lisanduv info võimaldab parendada ja lihtsustada elu. Hea näide on spordivaldkond, kus sportlased, treenerid ja ettevõtted vajavad järjest rohkem informatsiooni sensoritest, et jälgida, hinnata ja parendada sooritusi. Käesolev töö käsitleb ühe asjade interneti toote disaini, arendust ja realiseerimist, mis sobib spordirakendustes kasutamiseks.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 66 leheküljel, 5 peatükki, 37 joonist, 6 tabelit.

List of Abbreviations and Terms

IoT	Internet of Things
IoTSports	Internet of Things in Sports
ITPD	Interaction, Things, Processes and Data
I^2C	Inter-integrated circuit communication bus
6LoWPAN	IPv6 over Low power Wireless Personal Area Networks
BLE	Bluetooth Low Energy also known as Bluetooth Smart
GPIO	General Purpose Input/output
USART	Universal Synchronous Asynchronous Receiver Transmitter
SPI	Serial Peripheral Interface bus
Wearables	IoT devices that can be attached to clothing and footwear
Patchables	IoT devices that can be patched onto other objects
Implantables	IoT devices that can be implanted. e.g. under the skin
OSI	The Open Systems Interconnection model
API	Application Program Interface
SoC	System on Chip
OPAMP	Operational Amplifier
ADC	Analog-to-digital Converter
DSP	Digital Signal Processor
SDA	Serial Data signal line
SCL	Serial Clock signal line
CLK	Clock signal
PCB	Printed Circuit Board

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1 Introduction

The Internet-of-Things (IoT) revolution is driving new products and processes development in the fields of medicine, robotics, sports, remote monitoring, etc. Some important requirements in wireless sensor nodes are: to eliminate the use of wires, expand sensor options, improve mobility, and limit power consumption while remaining non-invasive [1].

To achieve these requirements, IoT product manufacturers are relying more on low-power communication protocols such as ZigBee, 6LoWPAN, and BLE; multi-GPIO controllers, and increased miniaturization of integrated circuits. The sensor nodes that are produced to meet these requirements give the added advantage of flexibility and expandability. As a result, the product life cycle can be reasonably altered to meet new market requirements in sports, fitness, health, home automation, inventory management, etc.

In this work, a sports and fitness IoT product will be considered. The product has very useful sensing capacities. New application areas for the existing product will be the focus of this work. In the following sections, some technical aspects related to modifying and expanding the functionality of the given product will also be analyzed.

1.1 Problem Statement

In this section, the problem which this work addresses will be presented. The existing system, developed by ELIKO Technology Competence Center, is a sports IoT device which has multi-sensor capabilities like motion sensing, in a single wearable node. This is possible because the Bluetooth Smart communication controller CC2541, on which the system is based, has multiple general purpose I/O pins and communication interfaces like USART, I^2C and SPI [2]. As a result, multiple micromechanical sensors have been integrated into the existing system and thus, multiple sensor information can be collected from the node and sent wirelessly to a sensor network monitor or controller.

The existing sensor capacities already make the existing device very viable IoT equipment for sports and fitness. However, a further sensor need has been highlighted. This work will therefore focus on extending the sensor functionality of the existing system.

In summary therefore, this work will aim to achieve the following:

1. Develop a force sensor module that can be included into the existing system.
2. Maintain a low energy consumption profile for the entire system.
3. Research and present implementation considerations for using the force sensor module in boat rowing.

1.2 Description of the Tasks Solved

These objectives presented in 1.1 above will be addressed by performing the following tasks:

1. Design and develop a low-power compact force sensor module as an expansion to the already existing system.
2. Deploy the developed sensor and test its suitability in the defined application.
3. Document and present the results of the experiments.
4. Research and present possible implementation considerations for the relevant application.

1.3 Thesis Structure

This thesis work is presented in five (5) different sections.

In Section 1, introductory information related to the objectives of the thesis work is presented.

Section 2 covers relevant background details related to the Internet of Things (IoT) product development. Specific products related to the existing system and sports applications in general are considered. Finally, the existing system is reviewed followed by a justification of the need and relevance of this work.

Section 3 starts with an overview of possible force sensing techniques. Specific information related to the used method is also given. Every hardware developmental work related to the force sensor is covered in details in this section.

In section 4, the developed device is configured and tested. The results of these initial experiments are presented and analyzed. Implementation considerations in the rowing application are also reviewed.

Section 5 concludes the work and gives insight into possible future work to improve the sensor.

2 Background of the Work and Literature Review

Relevant background information related to the work will be presented here. Firstly, a brief description of how the Internet-of-Things has evolved for sports and fitness applications is generally considered, and then the existing system is reviewed in relation to the extension of functionality that this work covers.

2.1 Key Aspects of IoT System Development

In this section, the underlying considerations in IoT systems development are considered. These key aspects explain how an IoT system is a combination of interaction, things, processes and data. This relationship is considered as it forms an important factor in developing new IoT systems and in extending the function of existing systems as is done in this work.

Today, the Internet of Things (IoT) is bringing devices together. It is usually made up of smart machines connected with other machines, objects, infrastructures, environments and databases. These connections generate large volumes of data which can be reduced to useful information [3]. IoT is not vertical in nature but lateral [4]. Applications will typically cut across every industry.

This lateral nature of IoT and the capacity to connect dissimilar devices together is driving the rapid increase in the number of “things” connected to the internet. In 2010, 12.5 billion devices were already connected and the number is expected to surpass 25 billion before 2020 [5], [6]. Lateralization of data mining and information management is reducing demands on specialists and experts as ordinary users are getting more help in analyzing available and increasing data more readily available through various platforms such as wearables in sports and health applications [6].

The architectural framework for Internet of Things in sports and health applications is based on interaction, things, processes and data (ITPD) [7]. Data is generated when “things” interact with each other in well-defined processes.

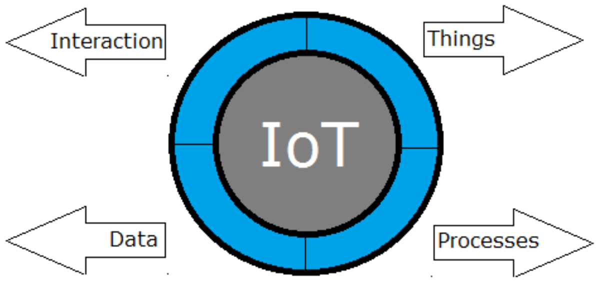


Figure 1. IoT ITPD Ring

An architectural framework based on a layered approach has been developed. This is summarized in the figure below. Similar to the OSI model, it has a bottom-up approach from the sensors up to the user applications [7].

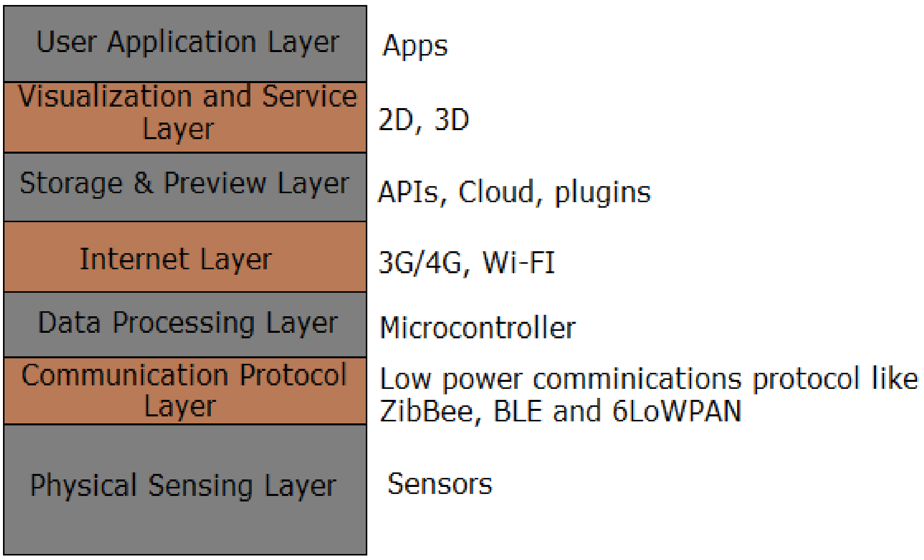


Figure 2. IoT Framework Layered Model

In this work, the focus will be on the physical sensing layer where sensors that can measure physical quantities are developed and implemented. Typical quantities measured in IoT applications are temperature, position in space, acceleration, impact, pressure, etc. Several considerations on size, power consumption, reliability, noise immunity, etc. are made at this layer.

As integrated circuit (IC) technologies improve, chip sizes have become smaller. This has enabled the development of powerful but small ultra-low power processors, sensors, and wireless communication devices. Similarly, technological improvements to cloud computing, big data analytics and efficient energy - especially with better energy harvesting methods and wireless power transfer (WPT), are driving the development of personal area networks (PANs) and body area networks (BANs) in IoT as wearables, patchables and implantables [8].

A wearable IoT device can be attached to a piece of clothing worn by an athlete or a person of medical interest. Such devices can also be worn directly as wristbands or sun glasses for example. This field of IoT devices is finding more and more applications in health and wellness monitoring, safety monitoring, home rehabilitation, virtual reality in gaming, early detection of disorders, auto-identification, retail, sports and fitness, etc [9]-[11].

2.2 Some Applications of IoT in Sports and Fitness

A few recent IoT products in sports and fitness will now be reviewed. The extension that this work covers will be justified by the limitations related to existing products and the existing system that forms the basis of this work.

The data that can be harvested in IoT is dependent on the sensors present. Hence, the applications of IoT devices are usually based on the possible interaction of processes with the specific sensors present [7]. The Internet-of-Things is finding more and more applications in sports and fitness. A smart device embedded with accelerometers, gyroscopes, magnetometers and pressure sensors, on the wrist of an athlete for example, can help to count steps, and track calories burned, and monitor heart rate. In health and wellness, IoT is enabling the implementation of wearables and patchables for the management of diseases. Taking advantage of the lateral approach of IoT also ensures that medical attention for the aged and the general population will be cheaper and easier to manage with these new developments [6], [11] - [13].

Currently, most electronic manufacturers are making huge investments to be at the forefront of this emerging market. More and more sensors are being patched onto sports gears and equipment. Some very recent developments are:

- **Intel's Curie processor**: Intel is shifting their data source from humans to things. At the recently concluded ESPN's Winter X Games (end of January 2016), the Intel's Curie processor was embedded into the snowboards providing data related to in-air rotations, jump height, and distance. This huge amount of data can provide performance information for analyses as well as to help improve players' performance [12].

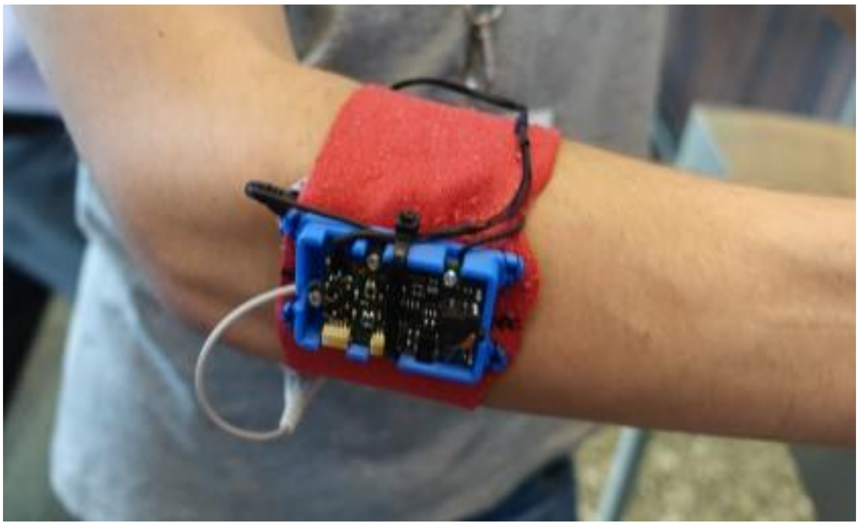


Figure 3. Smart Devices for Sports and Fitness - Intel's Curie processor is used on IoT Equipment in Sports [14]

In Live Sports, Intel's freeD technology is set to provide full 360 degrees video while the game is on. The development of Radar Pace sunglasses, to be launched later in 2016, is Intel's solution for a smart fitness and exercise coach.

- **Zepp Labs' Sports Equipment**: Zepp Labs have developed sensors that provide swing information and 3D visualizations in golf, tennis, baseball and softball [15]. Using two accelerometers and a 3-axis gyroscope, this sensor which is fitted to a glove can collect information of about 2000 swings and communicate same over Bluetooth 2.1 to a proprietary mobile app.

Figure 4. Smart Devices for Sports and Fitness - Zepp Labs Device for Golf [16]

- **Sony’s Smart Tennis Sensors**: Sony Corporation has developed Smart Tennis Sensors that can be embedded into compatible tennis racket handles. These can tell if a shot is forehand, backhand, serve or smash. It also gives information about the ball speed, swing speed and ball spin. The sensors included are a 3-axes motion tracking sensor and a vibration sensor [13]. As shown in the figure below, the sensor is attached to the handle of a compatible racket.

Figure 5. Smart Devices for Sports and Fitness - Sony’s Smart Tennis Sensor [17]

An earlier development in similar application area is the Babolat’s Pure Drive Play racket equipped with InvenSense motion sensing system.

- **Adidas’ miCoach**: Adidas have developed the miCoach SmartBall, shoes and wristwatches for football. These can track how the ball is struck, its speed, spin and flight path [13]. Included sensors in the ball are a 3-axes accelerometer and a 3-axes gyroscope. Collected information can be viewed on the accompanying mobile app via Bluetooth.

Figure 6. Smart Devices for Sports and Fitness - Adidas’ MiCoach Smartball [18]

- **Wilson's X Connected Ball**: In basketball recently, Wilson Sporting Goods Company released their Wilson X Connected Basketball that can detect shots made and missed in a basketball game [13]. It includes a 3-axes accelerometer patched to the ball and has some standard requirements to be met when it is used. This information collected is can also be viewed on a smart phone via Bluetooth.

Figure 7. Smart Devices for Sports and Fitness - Wilson's Connected Basketball [19]

- **Sensoria Smart Clothings**: Sensoria have a line of fitness T-shirts, sports bra, and socks. The socks are infused with textile pressure sensors while the tops come with heart rate sensors. The socks are used with an anklet that includes a 3-axes accelerometer and can communicate with a mobile app. Similarly the tops can be used with an optional heart rate monitor device that can provide communication with the mobile app via Bluetooth 4.0 [20]. Bodytech also has a new line of sports clothing including shorts and capris with accelerometers, gyroscopes, magnetometers and pressure sensors [13].

Figure 8. Smart Devices for Sports and Fitness: Sensoria's Fitness Socks [21]

- **LiveRowing Smart Indoor Machines:** This virtual rowing mobile app is based on the Concept2 indoor rowing machine. Using the LiveRowing Connect cable, the user connects the Concept2 machine to the LiveRowing mobile app on which the rowing motion from the machine can be displayed and matched against other Concept2 users around the world or a previous personal record. This way performance information can be tracked from stroke to stroke. This machine is expensive and as a virtual machine, it hardly gives real information regarding on-site rowing [22].

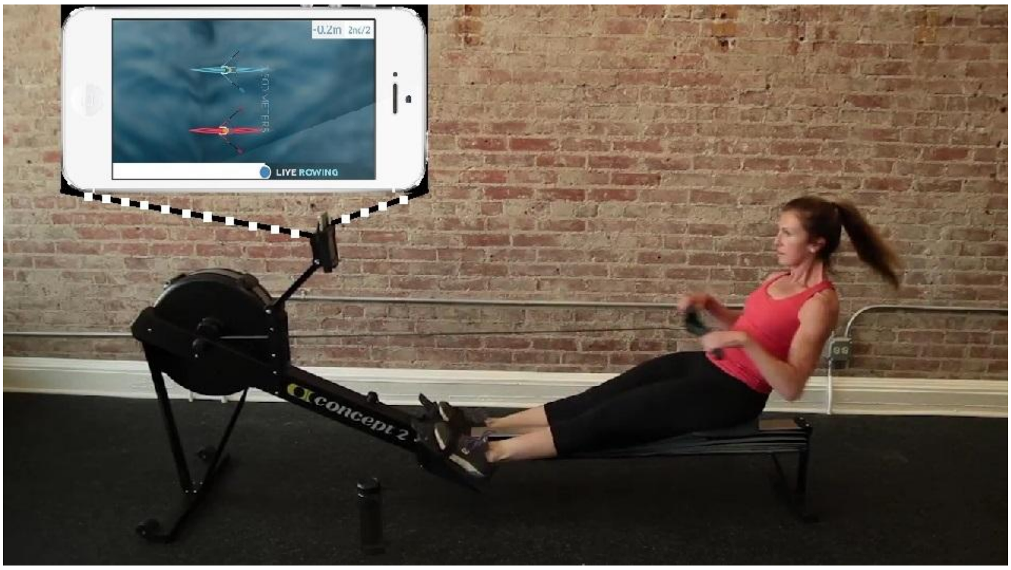


Figure 9. Smart Devices for Sports and Fitness: Concept2 Virtual Rowing Equipment [22], [23]

These smart devices are providing more and more data to improve performance, and make life much easier and safer. Using the gyroscopes and accelerometers, navigation information can be estimated using some proprietary positioning algorithms.

With a few recent IoT sports products already reviewed, the next section will go on to look at the existing system that this work is based on; included sensors, possible application areas and finally attempt to justify the need for the sensing capacity extension that was implemented in the work.

2.3 An Overview of the Existing System

In this section an overview of the existing system is presented. The primary IC which forms the core used in expanding the functionality of the sensor module is examined as also an overview of the key sensor capacities that already exist in the system is given.

The work is based on an existing wireless sensor node developed by ELIKO Technology Competence Center. The core of the system is based on Texas Instruments' (TI) CC2541 system-on-chip (SoC) [2] which has been integrated with a number of inertial and barometric sensors. The existing system is depicted in the block diagram below.

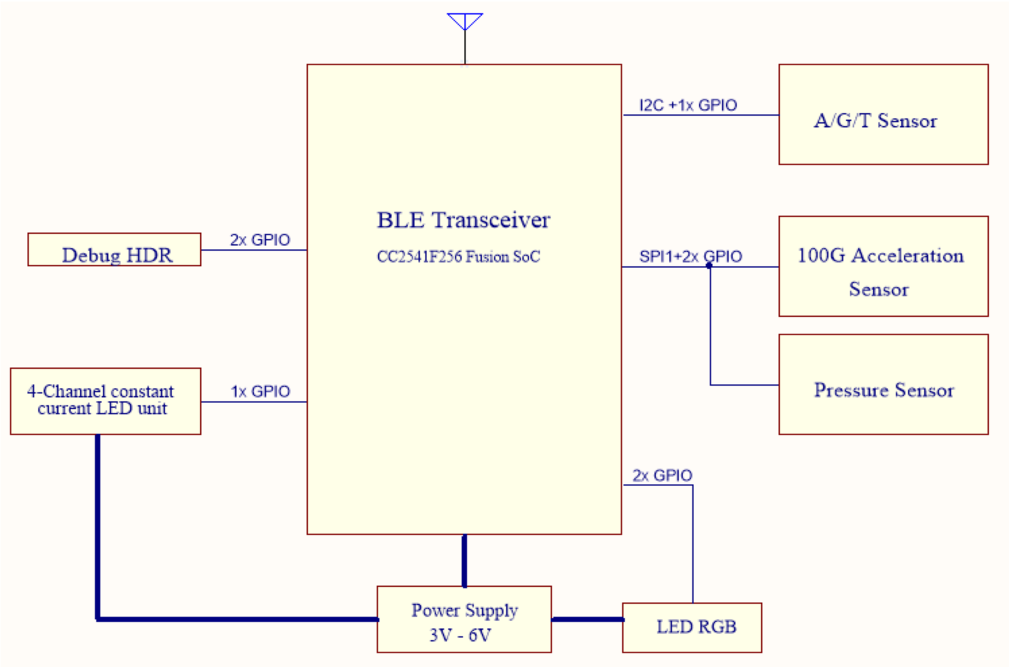


Figure 10. A Block Diagram Showing the Existing System

The CC2541 chip is connected to the sensors via I^2C and SPI interfaces. This fusion capacity of the SoC ensures that the final product remains compact and suitable for low energy applications. In the figure below, the existing system is shown.

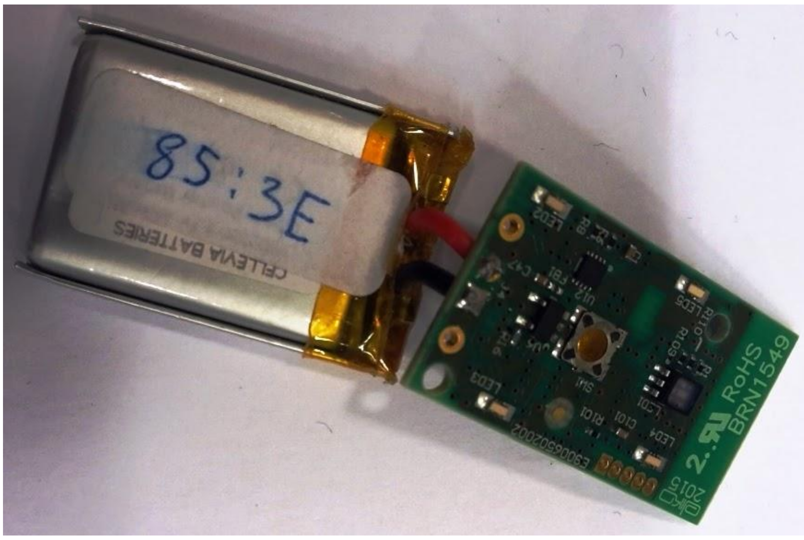


Figure 11. The CC2541F256 Sensor Module

The included sensor capabilities are:

1. Gyroscopes and accelerometers to provide positional and movement information,
2. Impact sensor for sensing g-force, and
3. Pressure sensor

The CC2541F256 core IC is a Bluetooth low energy and proprietary sensor fusion SoC that allows wireless sensor networks (WSNs) to be built with a minimal bill-of-materials cost. This is mainly because the CC2541 combines an 8051-type microcontroller with a powerful RF transceiver, and many other powerful peripherals. It also includes 256KB of programmable flash memory [2].

Depending on the power management register settings, the CC2541 can typically operate with a maximum output power of 0 dBm while consuming 16.8 mA with a supply voltage of 3V at room temperature [2], [24], [25].

The table below summarizes the main characteristics of the CC2541F256 chip.

Table 1. CC2541F256 Main Characteristics [24]

Manufacturer	**Operating Frequency**	**Data Rates**	**Interface**	**Power Consumption**	**Operating voltage**
Texas Instruments	2.4 GHz	250/500kbps, 1/2Mbps	I^2C GPIO	0.5A - 18.2 mA	2 - 3.6 V

2.4 Sports Applications of the Device and the Need for an Expansion

The included sensors already make the existing system very similar to the products reviewed previously in Section 2.2. When implemented on sports equipments such as baseball bats, golf clubs and tennis rackets, the sensor can provide swing, speed and position information. Similar applications include Zapp Lab's golf club sensor equipment and Sony's Smart Tennis Sensor [13]. In the same way, the developed system can be patched onto footballs and basketballs to track impact, spin, position and flight path.

With some algorithm development, the system can be used as a fitness coaching tool in a way similar to Microsoft's Kinect for the Xbox. This can also be useful for virtual reality applications in gaming for example where position information can be estimated with sensors deployed at appropriate locations around the gamer's body.

The impact sensor is well-suited for sports and fitness applications as well especially where safety is crucial. Some examples will be boxing, rugby and cricket. According to the United States Centre for Disease Control (CDC), from 2001 to 2009, the rate of the Emergency Department visits for sports and recreation-related injuries with a diagnosis of concussion or Traumatic Brain Injury (TBI) rose 57% among children equal to or less than 19 years. In 2009, there were about 248,000 children (less than 19) who were treated in the U.S. for sports and recreation-related injuries including a diagnosis of concussion or TBI [26]. In the movie Concussion, (2015), the suicidal effects of chronic traumatic encephalopathy (CTE) as researched by Dr. Bennett Omalu were depicted [27]. For such sports where physical contact is unavoidable, this sensor can be embedded in helmets and other sports equipment of interest to measure impact and keep the sportsmen within safe limits.

The pressure sensor can be used in outdoor sports applications. Mountain climbers for example, can get real time information regarding altitude and pressure. As weather equipment, the device can also be used to monitor weather conditions in remote areas and to evaluate the effect of weather on infrastructures and equipment.

In summary, the existing device is well-suited as a wearable or patchable device in sports and fitness in a way similar to existing products. Information relating to motion and positioning, spin and speed, impact and pressure can be collected in real time for performance evaluation, improvement and safety.

An in-depth evaluation of the existing system and available IoT sports and fitness products reveal an application that this work focuses on - the need to sense strain/force. In all the products considered, the strain/force metric which is very useful to understand how much force is enough force in a golf swing, for example, or how much force gives the best strokes in a boat row, cannot be obtained using the currently available products. The Concept2 machine is limited since it cannot be used in real life boat rowing situations. More importantly, while it gives information related to the number and period of strokes [22], it does not include vital information related to the angle and force of each stroke. Its high cost also means that it will not be available to every rower.

The CC2541F256 chip allows for more sensors to be integrated into the existing system. This will allow the development of a force/strain sensing module that can extend the function of the existing system in a way that achieves a real-life applicable system that can provide metrics including quantity and angle of force. This solution will also be cheaper since it can be deployed on any paddle of a boat, golf club, javelin, etc. In boat rowing for example, sensor data related to the amount of force (or strain) on the paddles and the direction of the stroke as the paddle goes into and out of the water can help players get real time feedback and thus improve performance.

2.5 Conclusion

In Section 2, key aspects considered in developing IoT systems were reviewed. A few recent applications of IoT in sports and fitness following the defined framework were considered and compared with the existing system that this work aims to improve.

In summary, the increasing use of IoT in sports and health applications was covered. The existing system and its possible application areas were also reviewed. As a compact module with an extensive array of sensors, the existing system will find wide applications in sports. A further review related to the underlying technologies of force sensing was also provided after attempting to justify the need for such an extension of sensor capacity. This extension, as presented, will make the existing system more useful as IoT equipment in sports.

In the section that follows, possible force sensing techniques will be reviewed briefly.

3 The Force Sensor Module

The force sensor module extends the functionality of the existing device. The sensor will provide force/strain information from sport equipment. The sensor finds several applications in sports. Some examples are estimating the amount of force in a javelin or golf club in use. Generally, any sports equipment in the shape of a bar, rod or beam can utilize this sensor in measuring force. In this work however, the focus of the design and other implementation considerations is on developing the force sensor for use in rowing.

A force is an action that makes a body accelerate from a rest position or change its state of uniform motion. The source of force can be internal or external depending on what elements are causing the action or reaction of the body [28], [29].

In general, there are basically five (5) methods of sensing force. These include:

1. Gravity based: Balancing the unknown force against the gravitational force acting on a known mass. Force in this case is equal to the known gravitational force. That is, force,

   $$F = mg \tag{1}$$

   Where m = known mass and g = gravitational force.

2. Acceleration based: Measuring the acceleration given to a known mass by the force. Here, force,

   $$F = ma \tag{2}$$

   Where a = acceleration of the body.

3. Flux based: Balancing the force against a magnetic field generated by a current-carrying coil interacting with a magnet. The force can be equated to the strength of the field.

4. Pressure based: Distributing the force over a specific area and measuring the pressure generated by the force.

5. Strain based: Measuring the strain produced in an elastic member by the unknown force.

Since this work is concerned with sensing force stimuli with micro sensors, an overview of possible micro force sensing options will now be presented. 'Micro' in the sense used refers to the size of the sensor element and not the amount of force measured.

3.1 Micro-Force Sensing Techniques

Some force sensing options that may be applicable in sports IoT devices are:

I. Piezoelectric method: deforming a piezoelectric crystal creates an electric potential that is proportional to the force applied. Some piezoelectric materials used are: quartz, Rochelle salt, ammonium dihydrogen phosphate (ADP), etc. This technique will be preferred in very precise applications [28]-[30].

II. Piezoresistive method: uses some forms of force sensing resistors (FSRs) for which resistance decreases as applied force is increased. The resistive materials can be conductive elastomers, Carbon felt or Carbon fibres. They have a linear transfer function over very small variations of force but are hyperbolic with larger variations. The method is cheaper but can be up to 25% inaccurate [28], [29].

III. Tactile sensor: useful in detecting touch, an area in space or the movement of an object relative to the sensor. Tactile sensors are mostly implemented as piezoelectric sensors using films like polyvinylidene Flouride (PVDF) or capacitive sensors in microelectromechanical systems (MEMS). They are also implemented using optical (using IR LEDs and detectors) and acoustic sensors (using sound signatures) [29]-[31]. Femtotools' FT-S microforce sensing probe is a capacitive sensor available on the market.

IV. Magnetoelastic method: based on changes to the permeability of a ferromagnetic material when a mechanical stress is applied to it. Some typical materials used are Alfer, Cekas, Ni-Fe alloys, etc. These sensors have a high resolution (nano-

Newtons) and are easy to design and mount. However, they are non-durable, sensitive to temperature changes and are prone to hysteresis errors [28], [30].

V. Strain gauge method: this is based on Hooke's law and measures the applied force in relation to the variation of resistance of the strain gauge. They are available as metal gauges or semiconductor gauges.

The methods above are mostly used with mobile apps. This trend is tied to smart phones being embedded with more and more micro sensors such as accelerometers and capacitive touch screen sensors. A number of force sensing applications are emerging which either work with external devices or as stand-alone force sensors. Some existing stand-alone apps are: iPhone's Sensor Kinetics and android-based Slackline Force [32], [33]. In-store reviews however, suggest these stand-alone apps are quite unstable in performance.

In Table 2 below, these methods of force sensing are compared against each other in terms of temperature dependence, sensitivity, dynamic range (ratio of largest to smallest force that can be detected), cost and simplicity of use. The cost includes the cost of the sensor, installation and calibration [34].

In comparing the above-listed techniques, it is seen that the silicon strain gauge technique gives the best performance at a comparably lower cost. This, in addition to its simplicity of installation, robust build among others, makes it a very good option in IoTSports. However, the method is highly dependent on temperature but this drawback is compensated for in this work.

Table 2. A Comparison of Force Sensing Techniques Applicable to Sports [35]

Force Sensing Technique	**Piezoelectric**	**Piezoresistive**		**Tactile**	**Magnetoelastic**	**Strain Gauge**	
Type		conductive elastomer	carbon felt or carbon fibres	digital tactile sensor array		metal gauge	semiconductor gauge
Linearity	linear	linear	very linear	linear			very linear
Durability	durable	very durable	durable	not durable	not durable	very robust	robust
Size	small	quite big	small	large area	small	thin	thin
Cost	costly	very cheap	cheap	costly	costly	cheap	cheap
Dynamic Range	wide	wide	wide	wide	wide	narrow	Fairly wide
Sensitivity	very high	low	low	very high		high	high
Temperature Dependence		high	high		high	high	very high
Simplicity of Use	complex	simple	simple	very simple	very complex	simple	simple
Remarks	frail electric junctions	linear over small range		no A/D conversions	prone to stray fields		low hysteresis

3.2 An Overview of the Force Sensor Module

Of all the force-sensing methods considered thus far, the strain gauge method stands out in the way it relates with the application this work addresses. The strain gauge method is ideal for sensing force in elastic members such as paddles, golf clubs, javelins, etc. Furthermore, the force sensor module does not require very precise measurements in small volumes. Instead, the purpose is to make measurements of a high resolution in a volume that may require readings from multiple dimensions (directions). Moreover, the strain gauge method as a well-researched technology can be designed to fully compensate for errors due to hysteresis and temperature changes.

In the figure below, a block diagram of the force sensor module is shown. The force sensor consists of the strain gauge which is deployed with a driving circuit. The signal from this input stage is then processed in a signal conditioning stage from where the output can be delivered to the existing system through the I^2C interface.

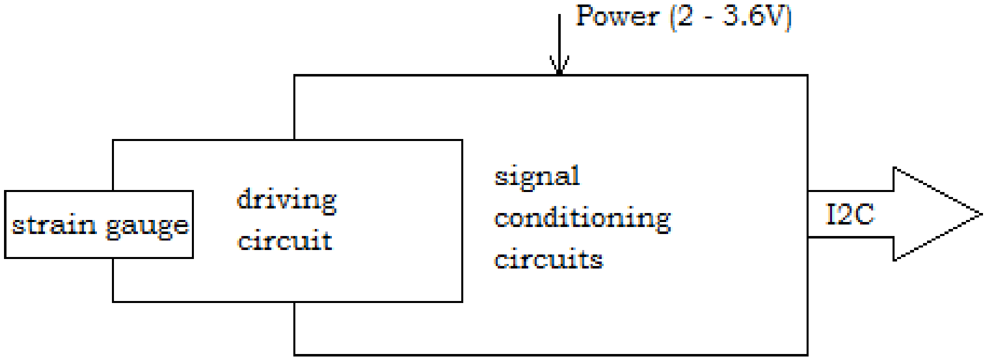


Figure 12. Diagram Showing the Building Blocks of the Strain-based Force Sensor

In the section that follows, relevant details of these blocks relating to the strain gauge method of force sensing will be presented.

3.3 The Strain Gauge

A strain gauge is made of a thin wire coiled in a snake-like grid pattern embedded in a thin film carrier [29], [36]. The grid is terminated with connectors soldered at both ends. The carrier is bonded directly to the material of interest so that strain is directly transferred to the grid. The changing strain corresponds to a change of resistance of the grid which can be used to estimate the applied strain. In the figure below, the typical construction pattern of a strain gauge is shown.

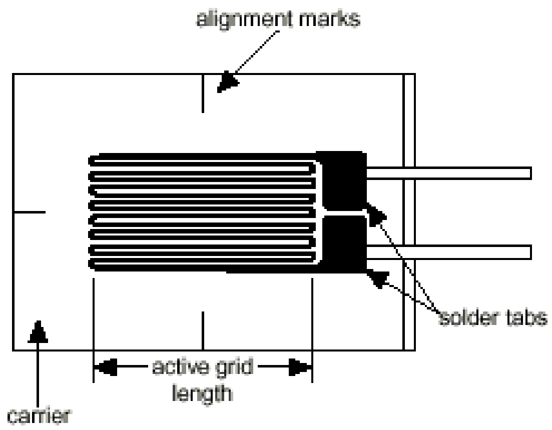


Figure 13. A Strain Gauge [37]

According to Hooke's law, the stress, applied to a member is related to the resulting strain, by the following relationship:

$$\sigma = \varepsilon E \quad (3)$$

E is a dimensionless quantity called the Young's modulus of the member.

For strain gauges, another factor called the gauge factor, e is defined. The change in resistance, R that results with an applied force is usually very small, typically a maximum of 2% [28], compared with the resistance, R of the strain gauge. The ratio of the change in resistance with the resistance of the strain gauge is given by,

$$\Delta R/R = e\varepsilon \quad (4)$$

For many materials, the gauge factor, e has a magnitude of approximately 2 [28].

In manufacturing strain gauges, some products are based on metal foil while others use Silicon. Metal foil strain gauges are usually cheaper and more readily available. However, silicon gauges are stronger, longer lasting, more accurate and better shielded from electrical noise [38]. Some manufacturers of the thin film strain gauges are HBM Test and Measurement (Germany), NanoLike SAS (France), Omega Engineering Inc. (United Kingdom), BCM Sensor Technologies (Belgium), Vishay Micro-Measurements (United States), Kyowa Electronic Instruments (Japan), and Tekscan Inc. (United

States). Typical nominal resistance values of the strain gauge are 120, 350 and 1000 [37].

3.3.1 Strain Gauge Selection Criteria

In selecting the appropriate strain gauge for a given application, a number of factors are considered. The order of consideration of these factors is not important as also the level of priority given to each factor [39]. Understanding the environmental and other operating conditions is vital for making the right compromises to meet the application requirements. Some of the operating constraints identified by Vishay are: accuracy, temperature, stability, elongation, cyclic endurance, application and environment [39].

In testing the force sensor module, HBM's 1-LY18-6/350 strain gauge was used. It has a nominal resistance of 350 0.35and a gauge factor of approximately, 2. Its operating temperature is between -70...200 degrees Celsius [40]. The connectors are Nickel plated Copper leads around 30mm long which also includes integrated solder tabs, around 1.5mm in length and 2mm wide. The mounted gauges are shown in the figure below.

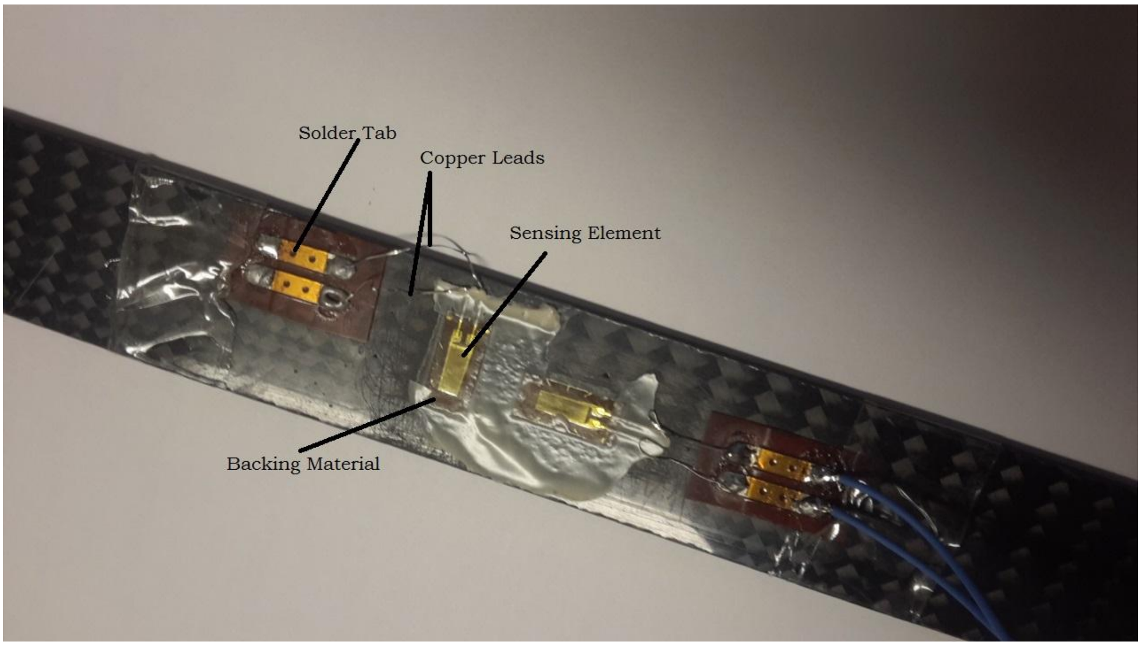


Figure 14. Showing Strain Gauges Mounted on a Composite Material

Below is a summary of some gauge properties that may affect the performance of the force sensor:

1. Strain-sensing alloys: The alloy used in the active foil of the gauge determines its performance to a large extent. Most common is constantan (Copper-Nickel). It is the oldest and most common material used. Between temperatures of -70°

and +200°C, it gives a low and controllable temperature coefficient in static strain measurements [41]. The 1-LY18-6/350 gauge uses Constantan foil in its sensing element. This is referred to as the Y-series by HBM [40]. For strains greater than 5%, annealed constantan (commonly called P-alloy) is used. Its high ductility gives it a higher range although it is less durable when constantly used with very high strains [39]. Isoelastic alloy, also known as D-alloy is preferred for dynamic strain measurements due to its better fatigue life and high gauge factor. To measure high temperature static and dynamic strain, Nickel-Chromium (K-alloy) is preferred [39]-[41].

2. Backing material: The common options are - polyimide and glass-fibre reinforced epoxy-phenolic. The latter is more commonly used since it gives better performance over a wide temperature range. Polyimide-backed gauges give more mechanical endurance during installation. This makes them more commonly used for general purpose gauges [41]. HBM's Y series of gauges has polyimide as the backing material [40].
3. Application: Two main strain test (or application) types are defined - static (long-term load conditions) and dynamic (short-term and varying load conditions) [41]. Over the same temperature ranges, static strain generally results to lower cyclic endurance.
4. Gauge Series: Different manufacturers define gauges using proprietary conventions. In general however, the gauge defines the strain-sensing alloy and backing material combination [39].
5. Gauge Length: The length of gauge used in application is determined based on the surface profile and length of the material on which it is mounted. Gauge length affects the sensitivity and elongation of the strain gauge [39]. Typical lengths of Vishay gauges are between 0.2mm and 100mm. The active element in HBM's 1-LY18-6/350 is 6mm long.
6. Gauge Pattern: This refers to the shape of the grid or number and orientation of grids in a multiple-grid gauge. It also includes the solder tab configuration and physical structures of the gauge [39]. For example, the solder tabs on a strain gauge should be selected such as to allow ease of installation on the intended location.

3.4 The Strain Gauge Driving Circuit

Due to the usually very small changes in resistance of strain gauges, the implementation circuits are designed to be sensitive enough to detect the smallest changes in resistance. This is usually done by designing the driving circuits using

1. Operational amplifiers (OPAMP) or
2. Bridge circuits

3.4.1 Strain Gauge Driving Circuit Using OPAMP

For a single strain gauge-only application, this configuration may be used in strain gauge applications. Tekscan Inc. for example, has designed very flexible force sensors with simple driving circuits based on OPAMP [42]. As illustrated in the schematic below, an excitation voltage, Vo, drives the circuit which has a feedback loop through the adjustable resistor, R_f. The strain gauge is connected to the inverting input of the OPAMP. The output, Vo, is given by,

Vo = -Ve * (Rf/Rs) (5)

Rs is the resistance of the strain gauge.

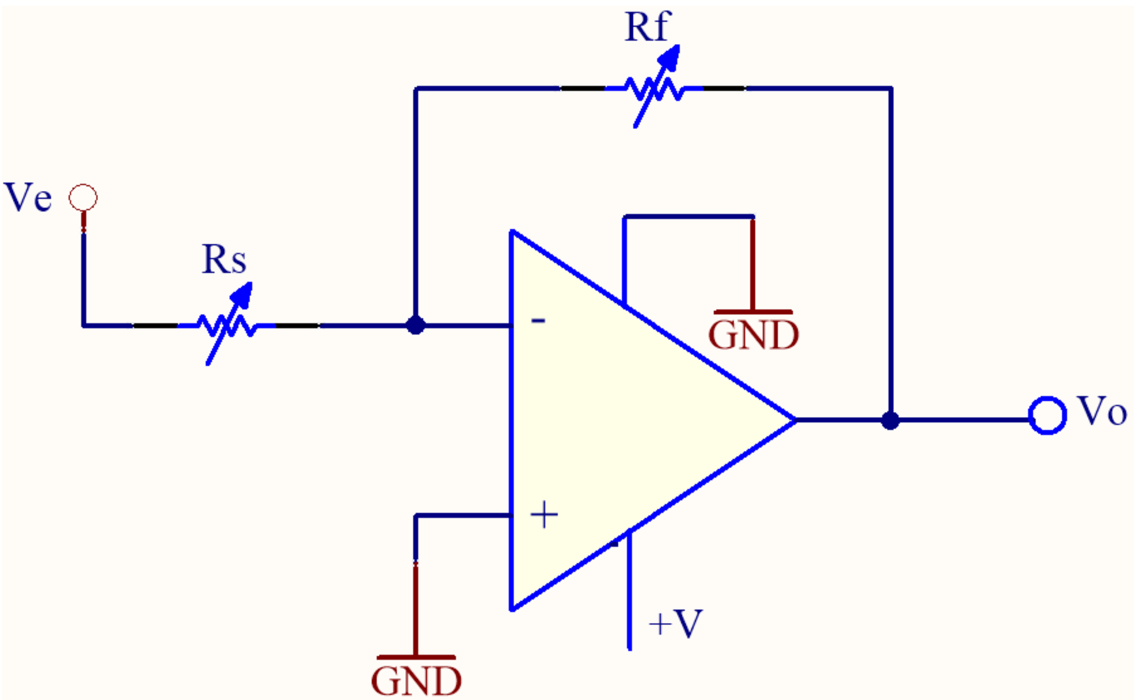


Figure 15. The OPAMP Driving Circuit for Strain Gauge Applications

The OPAMP driving circuit is limited to single-strain gauge applications (comparable to quarter bridge described in Section 3.4.2). It is mostly used with proprietary gauges. The single strain set up is more susceptible to noise and other environmental interference effects. To ensure flexibility and better performance in the force sensor module, this method is not used due to the above limitations.

3.4.2 Strain Gauge Driving Circuit Using the Wheatstone Bridge

The Wheatstone bridge method is more commonly used to measure small changes in resistance. The configuration is as shown below:

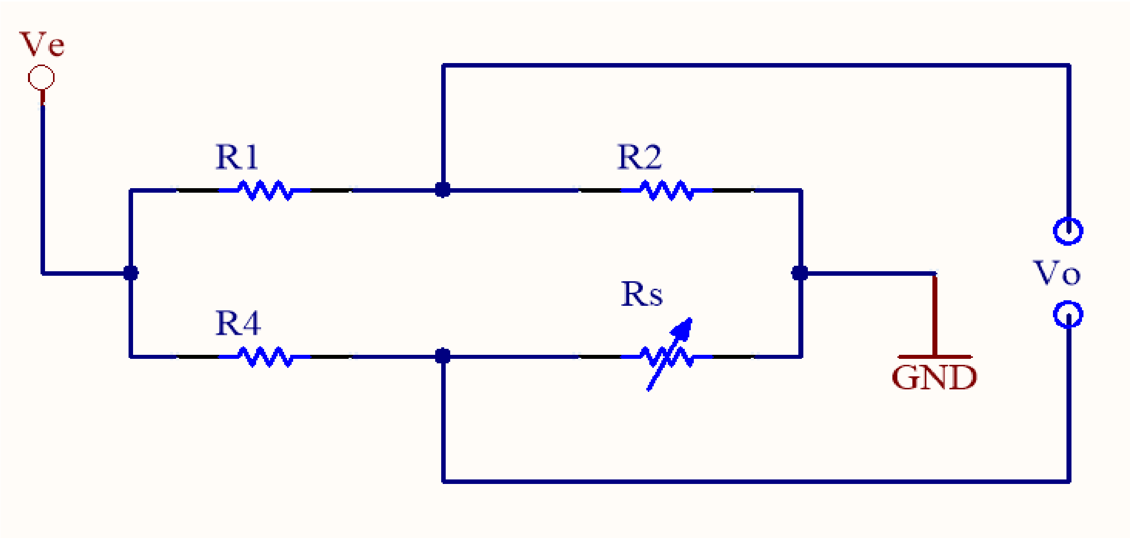


Figure 16. The Wheatstone Bridge Driving Circuit for Strain Gauge Applications

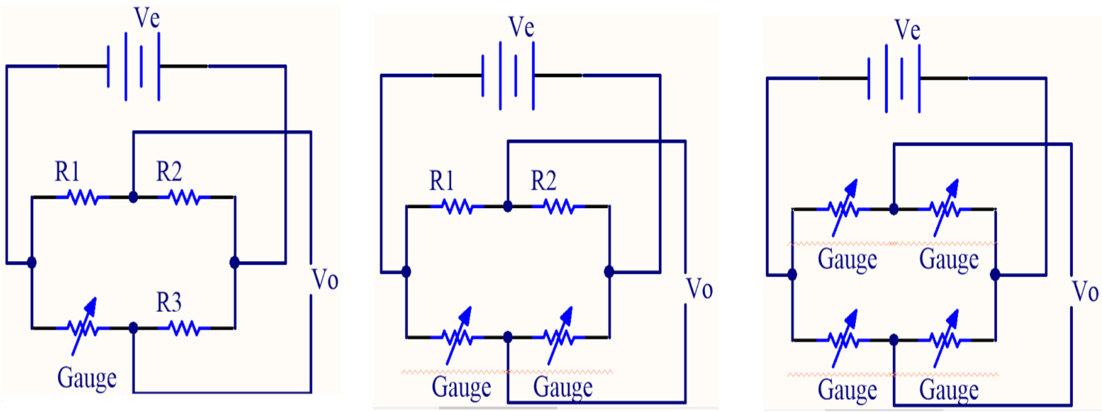
With the four resistors, R1, R2, Rs, and R4 arranged as shown, the output voltage Vo is related to the resistances and the excitation voltage, Ve by,

$$Vo/Ve = R1/(R1+R2) - R4/(Rs+R4) \tag{6}$$

Vo is also proportional to the ratios R1:R2 and R4:Rs. When the resistances are all equal, then Vo/Ve equals zero (balanced bridge condition) [36].

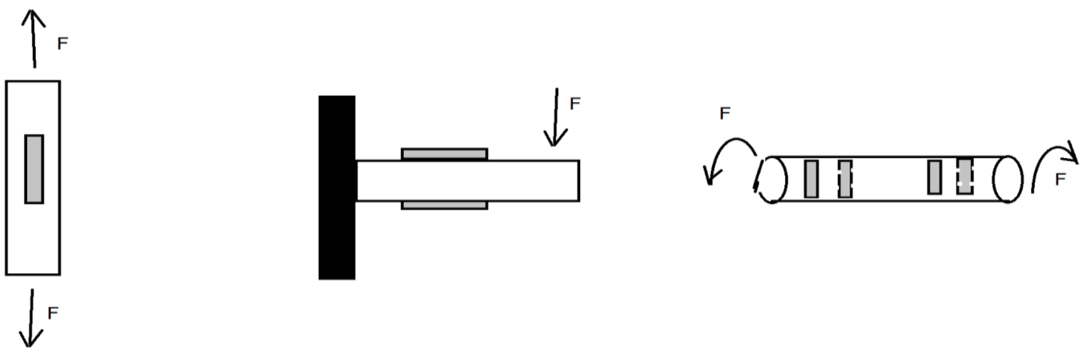
In the strain gauge implementation, one of the resistors (ideally Rs or R4 in the output branch of the bridge) is the strain gauge of known resistance. Hence the change of resistance, R in the strained member results in an imbalance of the bridge, thus producing an output voltage. This is a quarter bridge - only one of the four resistances varies. This set up can be used for a tension bar where force/strain is acting only in one direction. Since the strain gauge is prone to temperature effects, results from the quarter bridge are usually unstable. A typical solution is to implement a 'dummy' gauge where another resistor is swapped for yet another strain gauge which is unmounted but is exposed equally to the same atmospheric conditions as the active gauge to minimize changes due to temperature on the active gauge [36], [37].

To improve sensitivity if the bridge, the half-bridge implementation can be used. Two active gauges are mounted on the member in such a way as to detect the same stress in opposite directions but equal amounts. An example is a bending beam as shown where a bend in one direction correlates with a decrease in resistance of the gauge in that direction and the opposite for the gauge on the opposite side. This method also ensures that the effects of temperature are well-compensated for. The full-bridge which uses all four resistors as active gauges is a better solution for further improved sensitivity and less susceptibility to other interfering effects. This can be implemented in twisted shafts where multiple forces are acting in multiple directions [28]-[30], [36], [37].



(a) (b) (c)

Figure 17. The Strain Gauge in (a) Quarter Bridge, (b) Half Bridge and (c) Full Bridge Configurations



(a) (b) (c)

Figure 18. Strain Gauge Implementation on (a) Tension Bar, (b) Bending Beam and (c) Twisted Shaft

In practice, these force classes do not exist independently but are mostly superimposed with each other [36]. In the force sensor module developed in this work, the quarter bridge configuration is used. The force of interest in the boat rowing application are bending forces on the paddle similar to the bending beam fixed at one end in Figure 18(b) above. Further details of the design and implementation are presented in the following sections.

3.5 Implementation of the Data Acquisition and Signal Conditioners

The data acquisition and signal conditioner has to provide adequate compensation for offset, temperature effects, etc. This part of the module also has to perform signal processing functions such as analog-to-digital conversion and digital signal processing. These functions could be implemented using analog circuits like op-amps. Such a solution however, will be space and energy-consuming. Therefore, an integrated strain gauge signal processing IC is a preferred solution.

The main data acquisition and signal conditioning chip is the ZSC31014. This chip was chosen because it is a very powerful, low power signal conditioner that allows the force sensor module to communicate with the existing system using the digital I^2C interface. The ZSC31014 provides compensation for offset, sensitivity, temperature drift and non-linearity errors. It features an amplifier with eight (8) adjustable gain settings as well as a 14-bit analog-to-digital converter (ADC). It is available in a small SOP-8 pins package [43].

As a disadvantage however, the ZSC31014 chip has only a single channel. This means that a multi-axial solution will require as many ICs as the number of axes to be monitored.

The main features of the ZSC31014 are summarized in the table below.

Table 3. ZSC31014 Main Characteristics [43]

Manufacturer	System Clock	ADC Resolution	Interface	Power Consumption	Operating voltage
Zentrum Mikroelektronik Dresden AG (ZMDI)	1- or 4- MHz	14 bits	I^2C SPI	Low power sleep mode: <2A @$25^{o}C$ Active mode: ~70 - 120A @ 1MHz	2.7 - 5.5 V

In using the Wheatstone bridge configuration, some important considerations need to be made in collecting the signal from the sensor elements to obtain reliable measurements. Some important points to note are:

- **Bridge Completion**: Except if used in the full-bridge configuration, the strain gauges need to be in a complete Wheatstone bridge. In either the quarter-bridge or half-bridge, the signal acquisition and conditioning circuit usually uses high precision resistors to complete the bridge [37]. In the force sensor module, the strain gauge is implemented in a quarter-bridge. Most signal conditioning ICs available like the ZSC31014, are designed for full-bridge operation. Hence, three (3) high precision chip resistors were used to complete the bridge in the force sensor module as shown in the figure below.

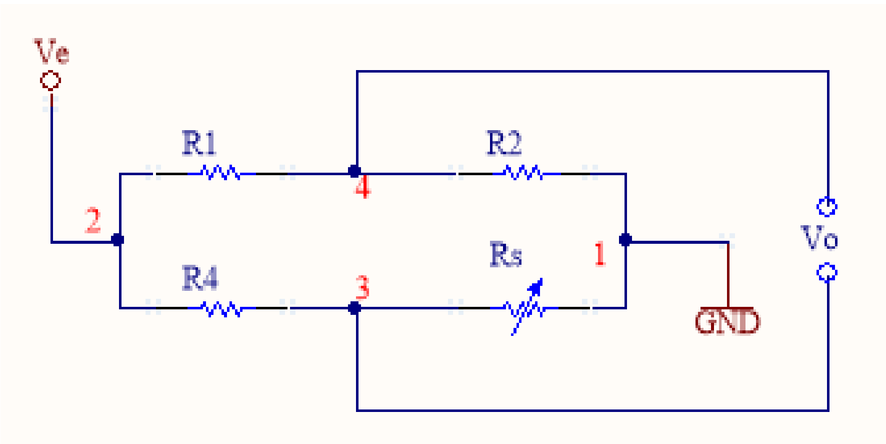


Figure 19. Completing the Wheatstone Bridge with Precision Resistors

The precision resistors R1, R2 and R4 are equal in resistance to the strain gauge resistance, Rs = 350ohms. The nodes 1, 2, 3 and 4 correspond to the connector pins. The strain gauge is connected between nodes 1 and 3.

- **Excitation**: Most signal conditioning circuit provide a constant excitation voltage of between 2.7V and 10V [37]. A tradeoff is made between having a voltage high enough to allow easy detection of the output voltage and low enough to minimize heating in the wires. In the force sensor module, an excitation voltage of 3.3V is supplied to the bridge through node 2.
- **Remote Sensing**: In cases where the strain gauges are far from the acquisition circuitry and excitation source, it becomes very important to provide adequate compensation for the extra resistance due to the length of wire. Typically, remote sensing wires are used to regulate the excitation voltage using negative feedback. To eliminate this extra resistance, the force sensor module is designed to be deployed on the device under test (DUT) e.g. rowing paddles. This will limit the length of wires attached to the strain gauge thus, compensating for improved precision of the system. This is possible because the existing system can communicate with the monitoring station remotely through Bluetooth.
- **Amplification**: Due to the small resistance changes, the output voltage from the bridge circuit is usually small, typically around 10mV/V of excitation voltage. Hence, some amplifier circuits are included in signal conditioners [37]. In the ZSC31014, amplification is done at the pre-amplifier stage. Eight (8) gain settings ranging from 1.5 to 192 are selectable by changing bits [6:4] in EEPROM Word $0F_{HEX}$ (B_Config register). The gain polarity can be changed on the EEPROM bit, Gain_Polarity [43].
- **Signal Processing**: Strain gauges usually have to operate in very noisy environments. This noise can be minimized using low pass filters. Digital signal conditioning circuits like the ZSC31014 perform filtering using software. The ZSC31014 features an analog-to-digital converter (ADC) and digital signal processor (DSP) that can process the converted signal [43].
- **Offset Nulling**: To limit zero offset voltages when the sensor is not loaded, some offset nulling is applied in most signal conditioners based on software or hardware (using a variable resistor) [37]. In the ZSC31014, the 12th bit in the configuration register is nulling control signal.

- **Temperature Effects Compensation**: Strain gauges are prone to interference from environmental effects most prominent of which is temperature. These are related to the physical properties of the active strain gauge element [36]. Except for the quarter-bridge configuration, temperature effects can be compensated for in hardware [36]. In the force sensor module using a quarter-bridge configuration, this temperature correction is done by the DSP [43].
- **Digital Communication**: Communication with the existing system is done through the digital I^2C interface. Digital communication elements in the data acquisition system include the ADCs and DSPs implemented in the ZSC31014. In the section that follows, the important aspects of the I^2C communication implemented in the force sensor module will be covered.

3.6 I^2C Communication

The I^2C interface on the ZSC31014 allows the force sensor module to communicate with the existing product. The system clock allows for data rates of 100- or 400-KHz to be selected on the I^2C. System clock setting of 4MHz allows I^2C data rates of 100- or 400-KHz while system clock frequency of 1MHz is usually used for 100 KHz communication only on the I^2C bus.

When the ZSC31014 starts in normal mode, it takes measurements from the bridge interface, converts and corrects the acquired measurements using a powerful ADC/DSP combination and writes the results to a register from where the I^2C bus reads the measurements. Implementing the ZSC31014 INT/SS pin as an interrupt is especially useful when the device has been configured to operate in sleep mode. It indicates when a new conversion is ready [43].

The START and STOP conditions of the ZSC31014 are depicted in the figure below. These conditions enable communication on the I^2C bus and helps increase efficiency by minimizing collisions.

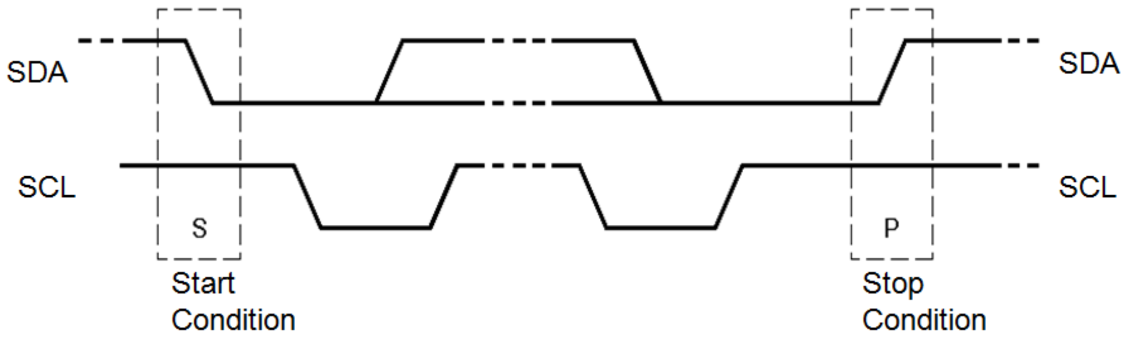


Figure 20. START and STOP Conditions of the ZSC31014 I^2C Bus [45]

The SDA line is the serial data line while SCL denotes the serial clock line. In the ZSC31014 like a regular I^2C bus, the clock can be stretched to allow complete transfer of data.

As a difference from regular I^2C, the ZSC31014 I^2C bus creates a communication error when a START/STOP condition goes without a transition on the CLK line. This error is only corrected by reapplying the correct START condition twice [43].

The ZSC31014 has a factory set 7-bit slave address of 28_{HEX}. In order to have multiple (3) gauge systems on the same PCB, a 3-channel I^2C multiplexer (TCA9543A) was added to the PCB. The table below summarizes the main characteristics of the device.

Table 4. TCA9543A Main Characteristics [44]

Manufacturer	**Clock Frequency**	**Number of Address pins**	**Interface**	**Power Consumption**	**Operating voltage**
Texas Instruments	0- or 400-kHz	2 (allowing up to 4 I^2C devices on the bus)	I^2C SMBus	Operation mode: 14A @f_{SCL} = 100-KHz, 3.6V	1.65 - 5.5 V

3.6.1 I^2C Device Addressing

Each I^2C device (ZSC31014 and TCA9543A) on the board has a 7 bit address. In communication, an 8th bit is included to indicate either a read (1) or write (0) operation.

Device 1 (U1): This will be addressed by the TCA9543A as slave 1110000 (70_{HEX}).

Device 2 (U2): This will be addressed by the TCA9543A as slave 1110001 (71_{HEX}). It can also bypass the TCA9543A master and communicate on the output as 010 1000 (28_{HEX}), taking its factory set address.

Device 3 (U3): This will be addressed by the TCA9543A as slave 1110010 (72_{HEX}).

3.7 Force Sensor Implementation Schematics Design

Apart from the ZSC31014 and TCA9543A, other devices included in the force sensor module are briefly described below.

Connectors: 1.27mm pitch pin headers were used for each input from the bridges and the output of the sensor module. The strain gauge inputs are applied through pins 3 and 4 on the P1, P2, and P3 connectors. The P4 connector has provisions for sensor IC address selection, common interrupt, SDA- and SCL-signal lines.

Interrupt Summator: Diodes were used to logically "OR" interrupt signals of three (3) ZSC31014 devices. When an interrupt occurs, all devices will be served in a sequence. A schematic diagram of the diode-based summator is shown below. The resistor, R27 will be installed when a single sensor configuration PCB is assembled.

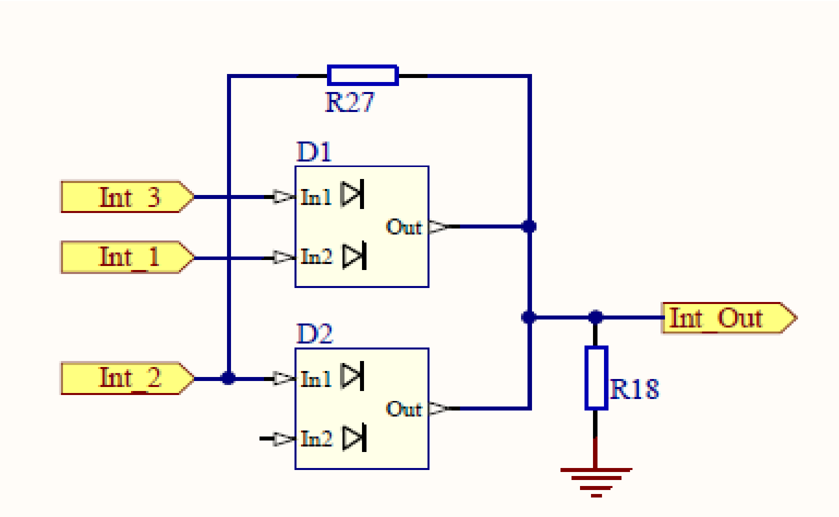


Figure 21. The Diode-based Interrupt Selector

Power Supply: All devices on the module can operate with supply voltages between 2.7 V and 3.6 V. This range of voltage matched the voltage requirement of the ELIKO device. For testing, the supply voltage is 3.3V.

The complete schematic of the force sensor module is given below.

There are 3 units of the ZSC31014 chip all connected to the I^2C switch chip. Device, U2 has the option to bypass the switch through 0-ohm resistors R19 and R20. This option is useful if only one of strain gauge is used in an application.

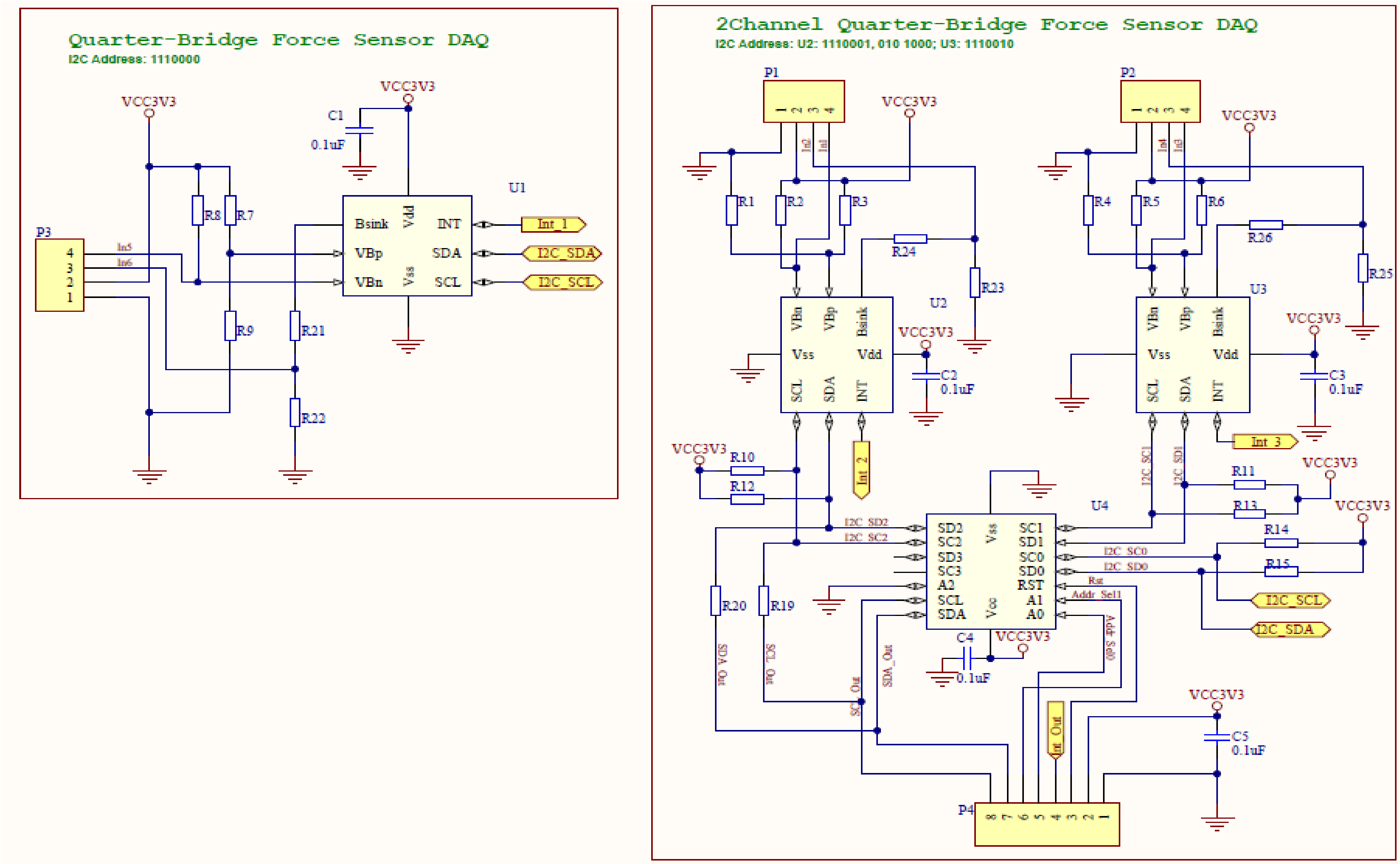


Figure 22. Complete Schematics of the Force Sensor Module

3.8 Force Sensor Implementation with Strain Gauges PCB Design

The PCB design of the force sensor module was done using Altium Designer 16.0. The design files are generated after annotations and compilation of the schematics. The main tasks performed at this stage are board selection and editing, parts placement, and routing. To design a PCB that can be manufactured at production, it was important to set the correct design rules. With the rules set, Altium Designer parts placement and routing could be done.

The PCB design of the force sensor module is a 2-layer board. The board dimensions are 40mm x 18mm to match the size of the existing board. To provide an electrically stable ground throughout the PCB, ground planes were implemented on both layer. From the design files, the gerbers were generated and sent to production. The figure below shows the artwork of the PCB design.

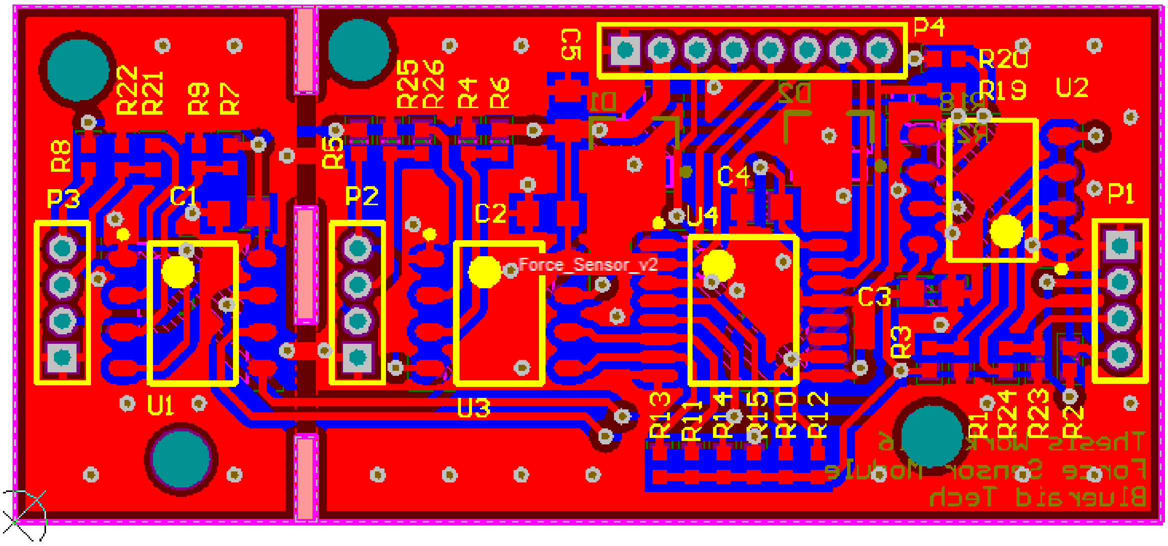


Figure 23. The Force Sensor PCB Design

3.9 The Assembled Force Sensor Module

Assembling the sensor module was done in stages to allow for the configuration and testing of each IC present on the board. In the figure below, the ZSC31014 chip has been soldered to the PCB and the connectors are all wired to configure and test the chip. In the following sections, the details of the configuration and testing of the sensor module will be presented.

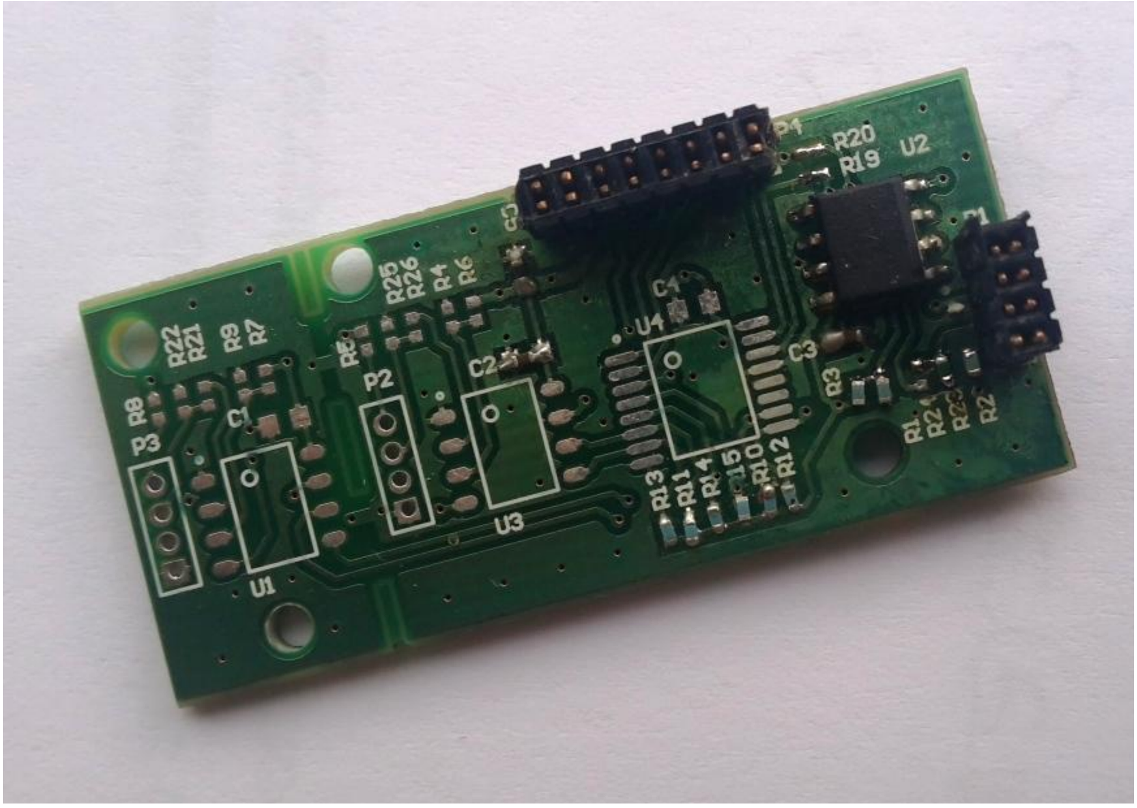


Figure 24. The Assembled Force Sensor Extension Module in Single Sensor Configuration

3.10 Conclusion

In section 3, important topics related to the development of the sensor module were covered. From gauge selection to the driving circuits, these component units were integrated into a force sensor module, manufactured and assembled. The main focus was to maintain a low energy profile and compact size to achieve a useful IoT device.

To conclude, the main principles used in micro force sensing were reviewed in general with particular focus on the use of strain gauges including key implementation considerations.

4 Implementation and Testing

In this section, details of the device configuration, test results and relevant implementation considerations will be presented. For simplicity, the single strain gauge sensor configuration was used during testing.

4.1 Configuring the Sensor ZSC31014 Chip

The ZSC31014 can only be configured over I^2C in the Command mode. At the clock frequency of 1MHz, a bit rate of 100 kHz will be supported. Commands can be sent to

- Calibrate/configure the device in Command mode,
- Start measurements from Sleep mode, or
- Read measurements from the device.

Calibration of the device involves assigning a unique ID, collecting data and calculating the coefficients. IDT provides special kits for calibration. Hence, this aspect is considered beyond the scope of this work and will not be covered.

Although the ZSC31014 device allows for a clock frequency of up to 4MHz, the 1 MHz frequency is preferred as it gives better noise performance. At power on, the device can be configured if it gets the Start_CM command that takes it into the Command Mode within a command window of 1.5ms at 1 MHz clock frequency. In the Command mode, configuration data can be read or written to the 2 bytes long EEPROM addresses of the device. Every command is 1 byte long. The figure below, illustrates the configuration algorithm. The device will start with the default/previous configuration settings if it does not go into the Command mode. This is the Normal operation mode.

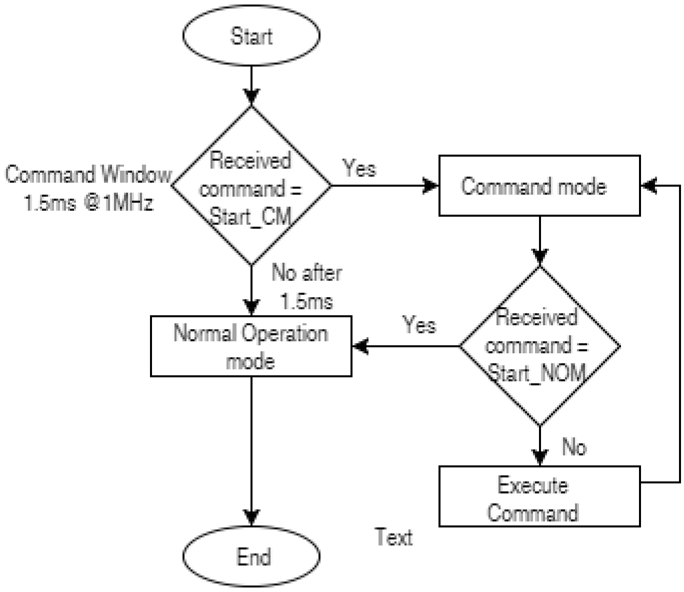


Figure 25. Flow Chart Showing the Power-on Operation of the Force Sensor Module

Each register address on the ZSC31014 is 16 bits long. Two (2) registers of interest in this work are 01_{HEX} where the device operating parameters are defined and OF_{HEX} where the bridge measurement settings are specified. The configuration data loaded into these registers are given in the table below.

Table 5. Configuration Register Settings of the Force Sensor Module

Register Address	Bit Range	Configuration Data	Description
01_{HEX} ZMDI_Config_1	2:0	001_{BIN}	Unchanged. Factory reserved
	3	1_{BIN}	Select 1 MHz clock
	4	0_{BIN}	Serial communication I^2C
	5	0_{BIN}	Sleep mode
	7:6	11_{BIN}	125ms @1 MHz clock
	15:8	00000000_{BIN}	Not changed. Used for other applications
OF_{HEX} B_Config	3:0	1000_{BIN}	A2D offset range of -½ to 1/2
	6:4	001_{BIN}	Pre-amp gain of 6
	7	1_{BIN}	Gain polarity of 1
	8	1_{BIN}	Unchanged
	9	1_{BIN}	Enables B_{SINK} to improve power saving
	11:10	10_{BIN}	For bridge input
	12	0_{BIN}	Enables nulling
	15:13	000_{BIN}	Factory reserved

These configuration settings were loaded over the virtual USB COM port to the ZSC31014 chip from a Windows PC. A USB-to-I^2C communication module was used to connect the PC to the device. The USB-to-I^2C interface provided with the device acts as the I^2C bus master. It controls the START and STOP conditions, as well as the slave addressing [46], [47]. This communication module is shown below. It is capable of supplying 3.3V power to the device during configuration and testing.

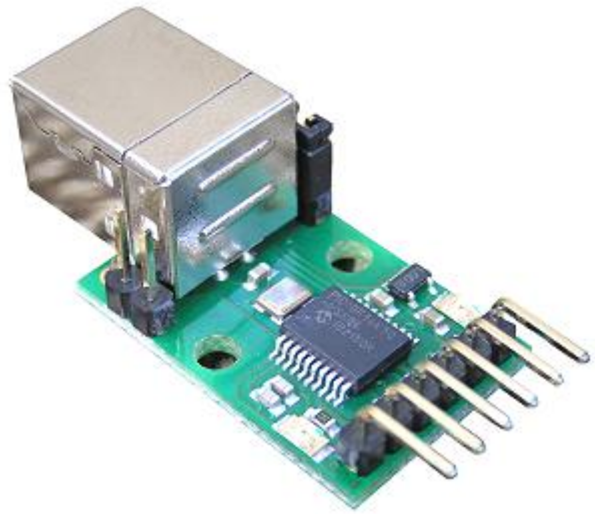


Figure 26. USB-to- I²C Communication Module Used for Configuration and Testing [46]

To configure the B_Config register for example, the following sequence of bytes is sent through the interface. The interface handles the device addressing and control sequences.

Table 6. Byte Sequence for Configuring the B-Config Register using the USB-to-I²C Interface

Byte	54_{HEX}	$0F_{HEX}$	19_{HEX}	$D0_{HEX}$
Description	USB-to-I²C module Write command	Target register address	First configuration byte	Second configuration byte

4.2 Software Algorithm of the Force Sensor Module

When the force sensor module starts, it loads the last saved configuration setting and will go into Normal Operation Mode if it does not receive the Start_CM ($A0_{HEX}$) command. In Normal Operation Mode, the device operates in either Update Mode or Sleep Mode depending on what read/write commands it receives. It is possible to send a Measurement Request or Data Fetch command to the device.

The Read_MR and Write_MR commands consist of only the 7-bit slave address and the R/Wr bit. These commands are used only in Sleep Mode to wake up the device, perform a measurement and DSP calculations before writing the result to the digital register where a Data Fetch can be performed to read the results. As a difference, the Read_MR command and perform other measurements (like temperature) while the Write_MR command can only perform bridge measurements.

There are Read_DF2, Read_DF3 and Read_DF4 commands, depending on when the master sends the NACK bit and STOP condition. The first two bytes include data of the bridge measurements while the next two bytes includes temperature measurement data. The number of bytes received determines how precise the results of the calculations are. In testing the force sensor module on the USB-to-I^2C interface, there are 255 data bytes for each Read operation. Calculations are done using the first 2 bytes which contain all bridge measurement information. With proper calibrations and good noise performance, the ZSC31014 can reach resolutions of close to 1 in 2^{16}.

Figure 27 below shows the software algorithm of the force sensor module.

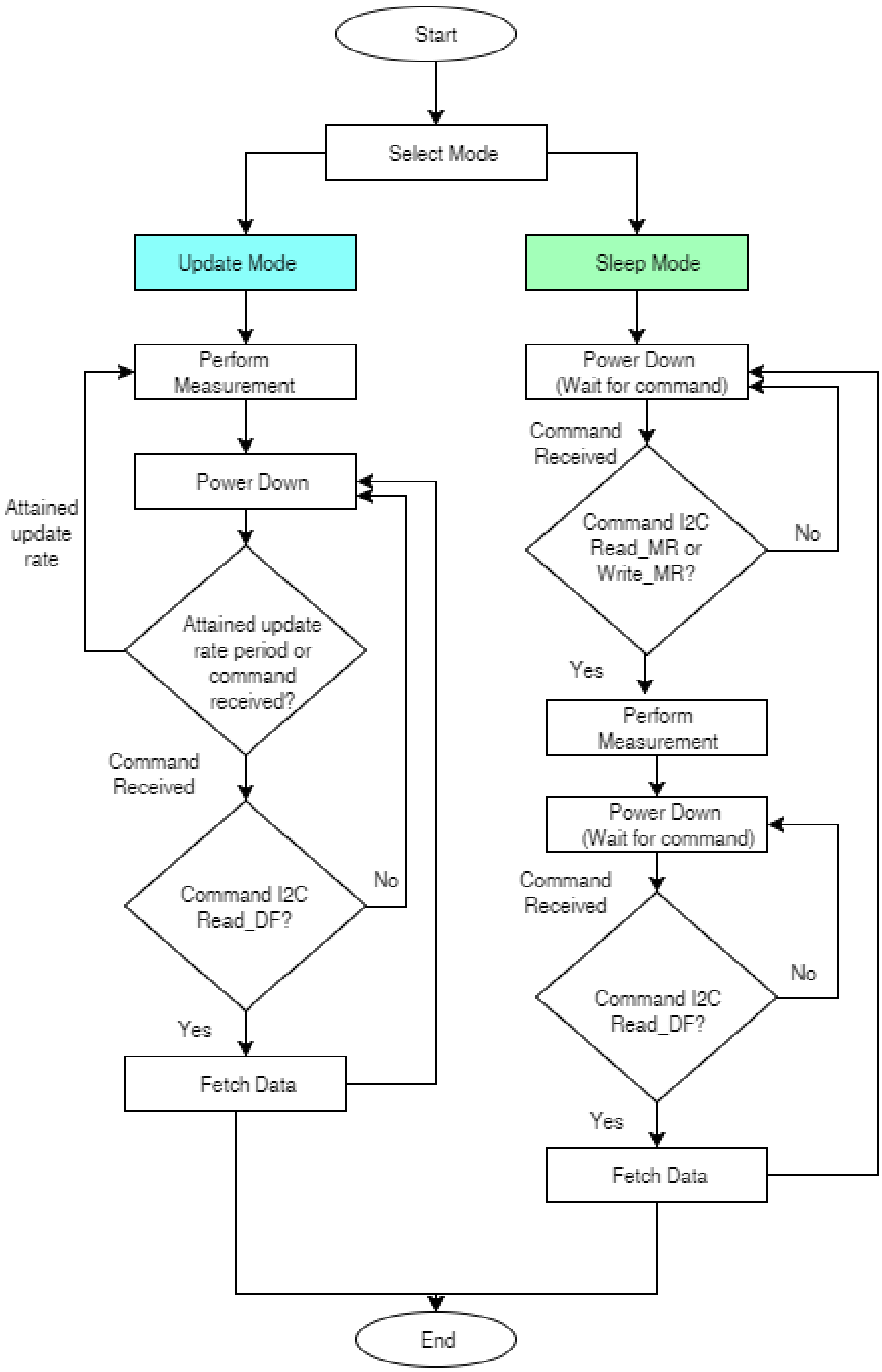


Figure 27. Software Algorithm of the Force Sensor Module in Normal Operation Mode

4.3 Testing the Force Sensor Module

In order to conduct the relevant tests, the boat rowing motion was simulated in the laboratory. The standard rowing sports uses rowboats and oars (paddles). These are as illustrated in the Figure 28 below. As can be seen, the paddle is attached to the boat at points C and E in the given illustration. The part from point A to B is referred to as the blade. Typically, the paddle is around 250cm long. The length might vary based on the height and weight of the rower. The handle is between the points labeled C and D. Weights are sometimes attached to the handle to balance the longer length on the outside of the rowboat.

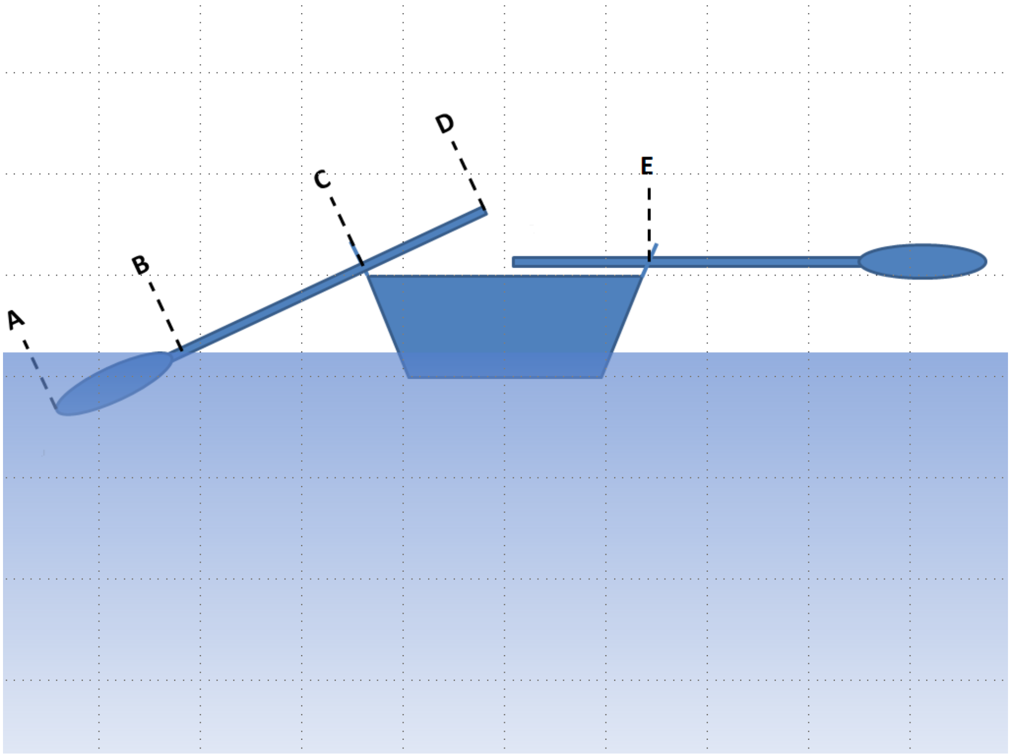


Figure 28. Illustration of the Rowboat and Oar (Paddle) [48]

4.3.1 Analysis of the Forces Acting on the Paddle in a Rowing Motion

There are basically two (2) motions (strokes) involved in rowing: paddle entry (when the blade goes in the water) and paddle exit (when the blade goes outside of the water) [49]. Going in and out of the water involves a forward stroke and a backward stroke both in a near horizontal loop. In the standard rowing sports, the seating arrangement is as shown in Figure 29 below and the rowboat direction is usually in the direction of the backward stroke. Each stroke takes approximately 0.8s [49].

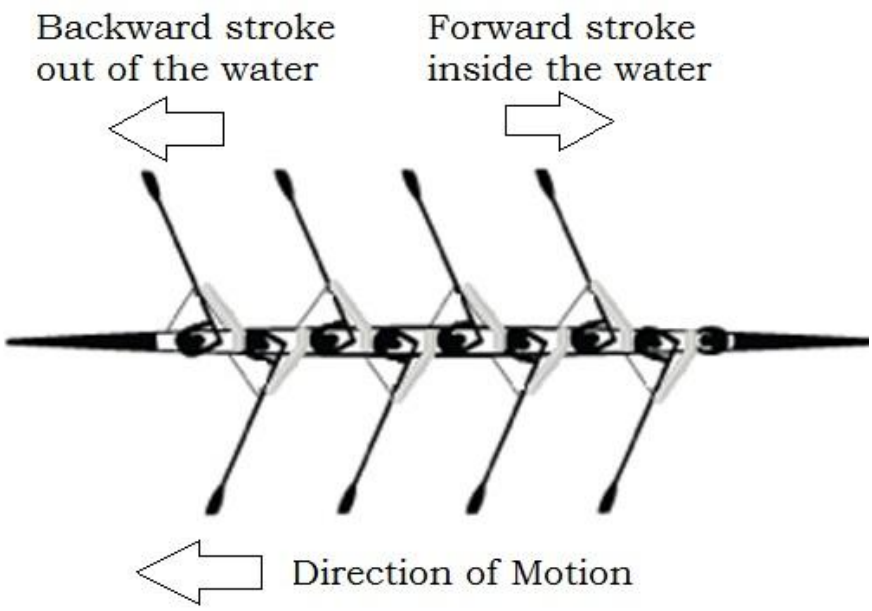


Figure 29. Illustration of Rower Positions, Paddle Directions and Direction of Motion [50]

There are three (3) identifiable force areas on the paddle:

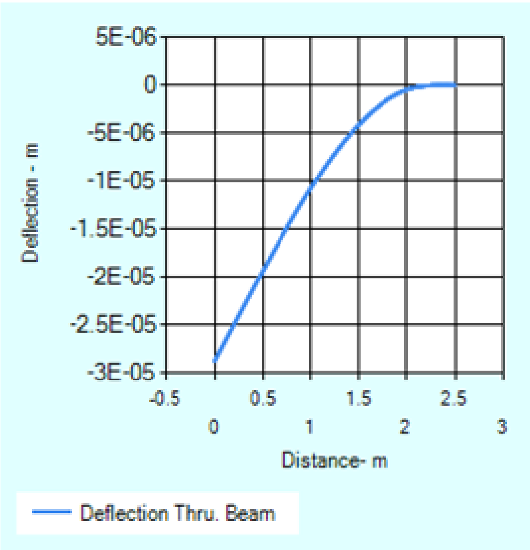
- Blade force,
- Handle force, and
- Pivot force

Figure 30. The Forces Present on a Paddle

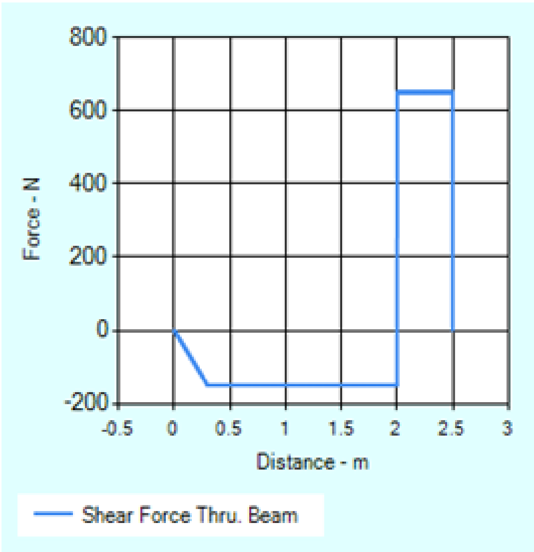
The force at the pivot is not very useful to this application since the strain gauges are fragile and are not designed to withstand direct contact. At the blade, the force sensor module will not be tolerant of the harsh physical conditions (entering and exiting the water) and the high accelerations present on long paddles used in standard rowing. Although the force at the handle takes the direct input of the rower more into account, it may also be limited by compatibility with different oars manufacturers (since the sensor may be integrated into the handle) and variations in handling positions of different rowers [51].

4.3.2 Placement of the Force Sensor Strain Gauges on the Paddle

Before identifying a suitable placement for the sensor device on the paddle, results of calculations on the mechanical forces present in a cantilever beam will be presented. These results are specified for a beam of length 2.5m (the approximate length of a standard paddle). The beam is fixed at one end, assuming a constant input from the rower in both upward and downward directions. This assumption closely models the forward and backward strokes of the rower. It is also assumed that an upward force of 80N acts at 0.5m from the fixed end (the pivot) and that a distributed force of 500N/m acts at the free end for a total length of 0.3m (the blade).



(a)



(b)

Figure 31. Results of Calculations on the Paddle Model: (a) Deflection through the Beam, (b) Shear Force through the Beam [52]

From the results of the calculations, it can be seen that the shear force is critically too high and will reduce the durability of the strain gauges. Away from the pivot and toward the blade, the shear force level is lower and stable while the deflection across the beam also increases, albeit in the negative direction.

In order not to overload the gauges, they can be placed mid-way between the points of maximum and minimum deflections while keeping the shear force minimal. For a paddle length of 2.5m and pivoted at 0.5m from the handle area, the region between 1m and 1.5m from the blade end should be ideal.

4.3.3 Placement Orientation of the Strain Gauges

Depending on the shape of the paddle and the handling of the rower, between 1 and 3 strain gauges can be mounted to capture all the forces acting on the paddle. The developed force sensor module includes three (3) strain gauge sensing elements.

In the tests one strain gauge placed laterally across the test paddle was sufficient since the composite material was thin and thus included mostly forces acting in one direction. This one gauge implementation can also be applicable in real life systems, where non-attached paddle is completely handled by the rower.

In more complex systems such as the competitive rowing sports where the paddle is attached to the rowboat, at least two (2) gauges placed at right angles and laterally across the paddle will capture most forces acting on the paddle. For higher precision, a third gauge is placed at 45° to the first two (2) gauges.

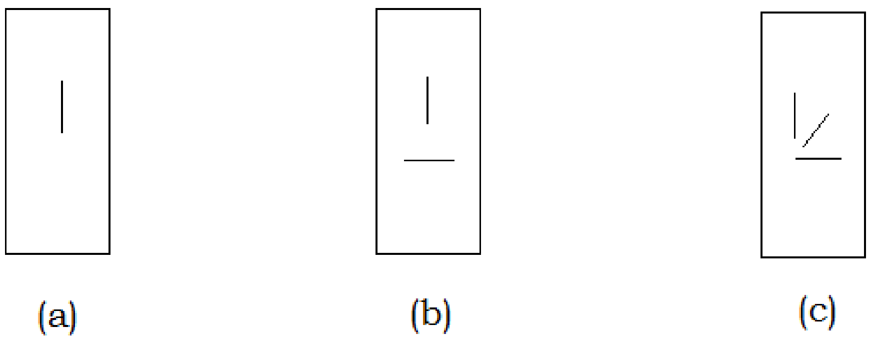


Figure 32. Strain Gauge Placement Orientations on Paddle: (a) Simple Un-attached paddle, (b) Attached Paddle, (c) High Precision Attached Paddle

4.3.4 Test Setup of the Force Sensor Module

To simulate the rowing motion and measure the associated forces, the setup shown in Figure 33 below was used. A single strain gauge was mounted on a composite member (thickness ~1mm, length ~ 250mm). The composite member was clamped at one end, pivoted on a knife-edge at about 20mm from the clamped end. At the free end, masses of 20g, 21g and 22g were applied.

The force sensor module which collects inputs from the mounted strain gauge was connected via COM port to a PC where the measurement data can be collected and analyzed. The USB-to-I^2C interface used does not log changing register contents. Hence, Eltima's Serial Port Splitter [53] was used to split to virtual COM port (VCP) to the USB-to-I^2C interface and the Eltima's Serial Port Monitor [54] for simpler data tracking. The following settings were applied on the USB-to-I^2C interface:

COM Port = COM1 selected

Device address = 0x50 (7 bit address 28_{HEX} + write bit)

I^2C clock frequency = 100 kHz

Registers to monitor = 00 (bridge data) and 01 (bridge data)

Figure 33. Force Sensor Module Laboratory Test Setup

The rowing motion was simulated by applying the masses in a period of about 2.5s. Each test session consisted of 10 periods.

4.4 Test Results

Results of tests carried out on the force sensor module will now be presented.

Measured power consumption:

Supply voltage = 3.28V

Average current consumption = 4.23mA

Measurement was done using a DT830D digital multimeter.

In the first three (3) sessions, the 20g masses were applied to the force sensor mounted to the composite-made test specimen (Figure 14, 33). It took approximately 2.5s to load and unload the gauge. During the measurements, an offset of 31_{HEX} was observed. This offset value was eliminated in the calculations on Matlab to have an initial value of 0. After these initial calculations, the mean value of the measurements also revealed the option to compensate for the uncalibrated device by applying a division by 2. The first three sessions are plotted on Matlab and presented in the graph below.

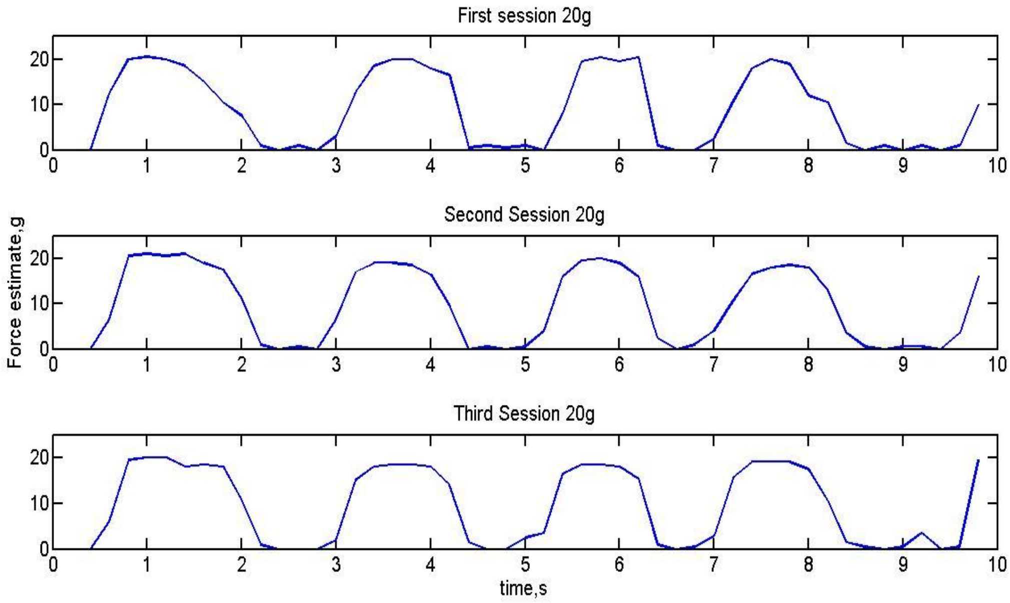


Figure 34. Chart showing a few Periods of the First Three Sessions with a 20g Weight

At an update rate of 200ms, it can be seen that the device captures very quick changes in the load value on the strain gauge.

Calculating the mean of these first three sessions and plotting them together in Figure 35 below, reveals a consistency in the force pattern. Thus, the force sensor module can be deemed up to around 80% accurate (maximum deviation from the 20g mark is 4).

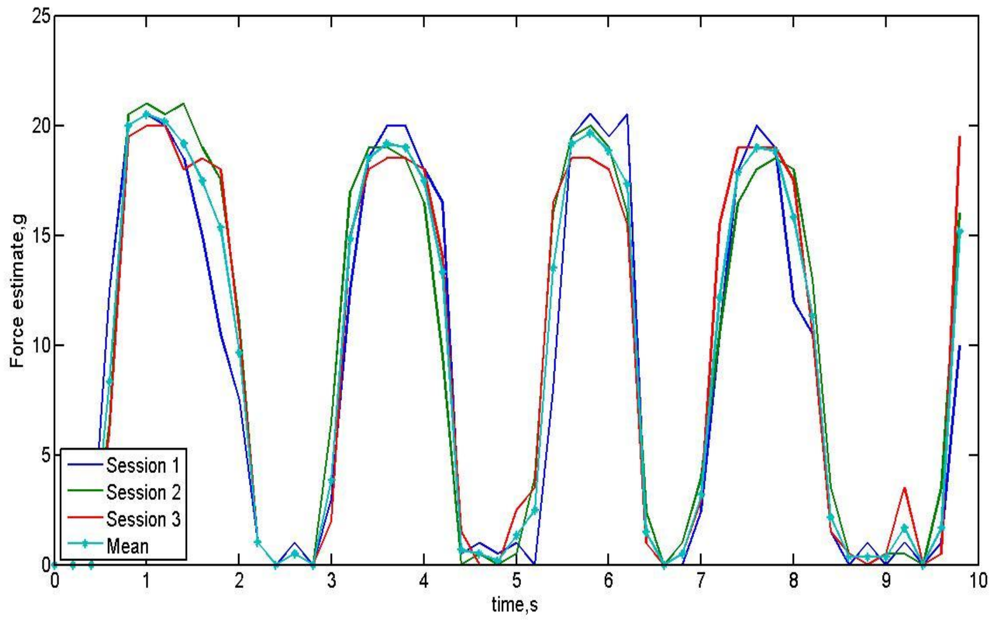


Figure 35. First three Sessions with 20g Weight and their Average Value

To estimate the resolution of the non-calibrated ZSC31014 device, two more test sessions were carried out with weights of 21g and 22g. As is seen in the figure below, the 22g goes above the 20g mark 75% of the time. The number is actually higher with a few more samples. This distinction is not very clear with the 21g weight.

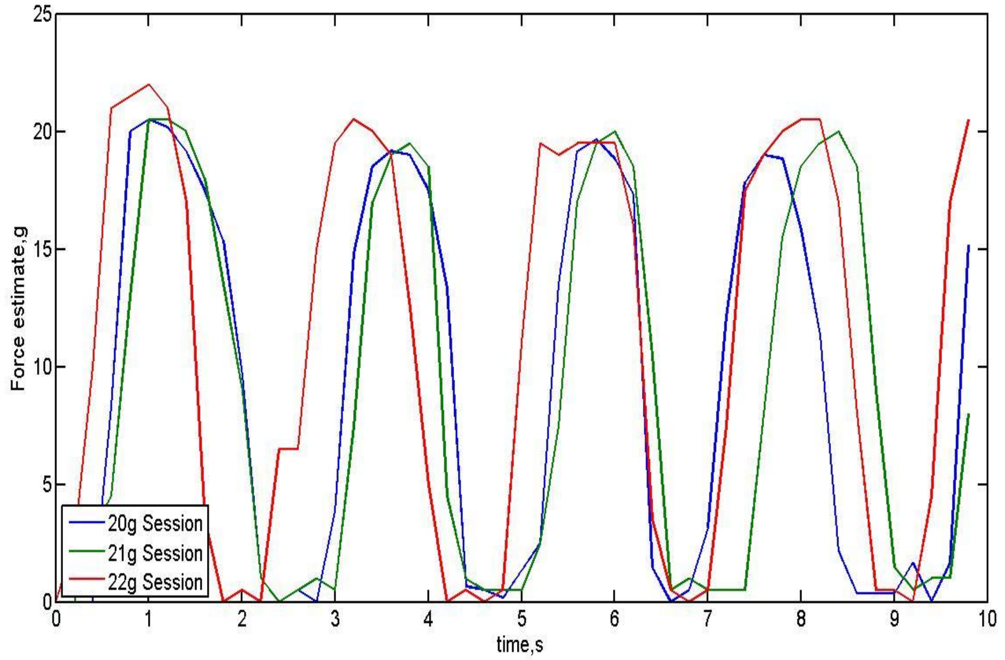


Figure 36. A Plot of the Sessions with 20g, 21g, and 22g Weights Showing the Resolution

In conclusion, the uncalibrated ZSC31014 gives the force sensor module a resolution of about 2g for this particular composite specimen used during testing. It will be possible to distinguish smaller changes in force after the ZSC31014 device has been calibrated.

To test the linearity of the data acquisition system, small displacements were applied to the composite with the strain gauge mounted on it. The applied displacement was increased in steps of 3mm. The response of the module after 5 steps is seen in Figure 37 below. As can be seen in the illustration, the force sensor module has a generally linear response.

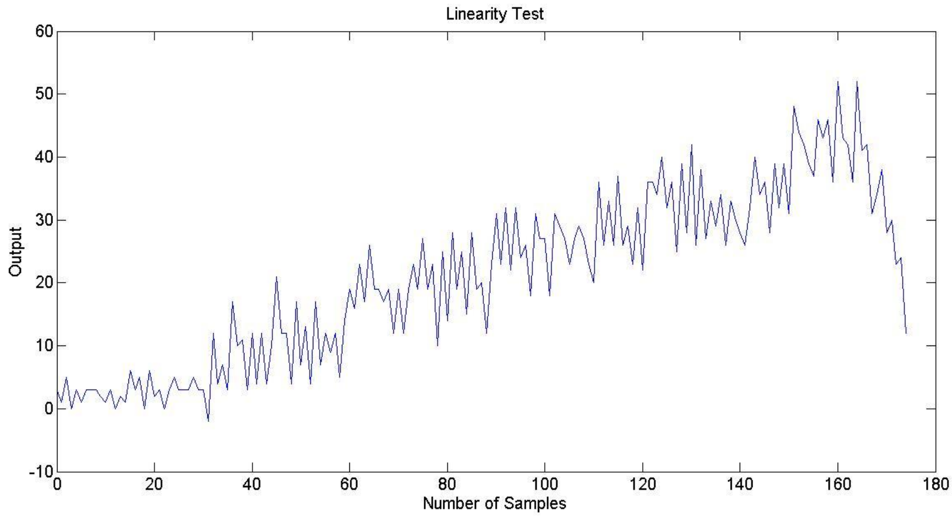


Figure 37. Linearity Response of the Force Sensor Module

4.5 Conclusion

Relevant details related to the configuration and implementations of the force sensor module were presented in this section. Information on the configuration of the primary measurement IC, ZSC31014 was given. Hardware considerations in implementing the force sensor module in the rowing application were also covered.

Finally, simulation tests for the rowing application were carried out and the obtained results were presented.

5 Conclusion and Recommendations

This Master's thesis work was supported by ELIKO Technology Competence Center.

Areas for possible further modifications and future improvements will now be presented.

5.1 Possible Modifications and Future Improvements

Due to time constraints, it was not possible to integrate the existing Bluetooth sensor device to communicate with the new force sensor module. This will be a very important area to cover since the sensor is more convenient after eliminating the use of wires.

To enable the sensor to work with all three (3) gauges in more precise applications, the I^2C multiplexer control software needs to be implemented as well.

One area that requires more study and development is the calibration of the ZSC31014 chip. At the moment, this calibration can only be done using the manufacturer's evaluation kit. It may be possible to make modifications to the designed sensor to allow for these calibrations to be done in the Command Mode. This development will increase the flexibility and usefulness of the ZSC31014 as the primary measurement IC on the force sensor module.

5.2 Summary and Conclusion

This thesis work describes a development work of a force sensor data acquisition module that can be integrated into an already existing IoT motion monitoring device developed by ELIKO Competence Center. The sensor can be used for rowing performance monitoring, where it can be attached to a paddle to provide real time information on the amount of force applied by the sportsman. This information will help to track and improve performance.

The developed and assembled sensor module was successfully tested in a single strain gauge configuration through a PC. Future work will be to modify the CC2541 microcontroller software to support the strain gauge data acquisition device.

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