March 10, 2016

Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, BC
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Re: ENSC 440/305W Design Specifications for P5 North Seeking Gyrocompass

Dear Professor Rawicz,

The document attached outlines the design specifications for the P5 North Seeking Gyrocompass. Our goal is to find the direction of true north within two degrees of accuracy, using a high performance MEMS gyroscope and self- leveling platform in order to aid in the navigation of large industrial ships.

This document outlines the technical details necessary for the implementation of an embedded system algorithm that manages the hardware and software components of the prototype phase of the P5 North Seeking Gyro Unit. In addition, the physical specifications and design pertaining to the self-leveling platform and electronics are also presented; with justification for design choices based on the performance, testing, and overall unity of parts when combined. A high level test plan is included to test the calibration of the gyro and determine the accuracy and consistency of the hardware and software components.

The specifications outlined in this document will serve as a guide for implementation of the prototype phase of the design of the P5. Features are described for the final product release model, however incorporation of these features will occur upon completion and testing of the P5 prototype.

The team working on this project consists of five fourth year engineering students: Katie Tse, Steven Hua, Justin Chan, Emma Chadsey, and Julie Atherton. If you have any questions or concerns regarding this document, please feel free to contact me at kkt21@sfu.ca

Regards,

Katie Tse
President
Notos

Enclosure: Functional Specifications for P5 North Seeking Gyrocompass

P5
North Seeking Gyrocompass

Design Specifications

Submitted to:

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Executive Summary

Gyrocompasses are a widely used navigational device for industrial ships. They are the most reliable method available for determining heading, and are also very accurate. Currently, mechanical gyrocompasses are used; these devices are completely sufficient, however they are expensive and large in size. With recent advances in MEMS technology, it is now possible to build a MEMS gyrocompass that will meet high enough standards to be used in the place of a mechanical gyrocompass.

This document outlines the design specifications for the P5 North Seeking Gyrocompass. The P5 is a MEMS gyrocompass designed with the intent of being used on an industrial ship. Its design can be described in terms of two subunits, the Self Leveling Platform and the North Finding Unit. The purpose of the Self Leveling Platform is to keep the North Finding Unit in the horizontal plane, and the purpose of the North Finding Unit, as the name suggests, is to find heading relative to true north. Key design choices made for this project are listed below, and are described in more detail in this document.

* Physical design of Self Leveling Platform

* Calibration method for North Finding Unit

The prototype version of the P5 has been designed using high grade components, similar to what might be used in the product release version. Details of the factors considered when choosing major components are included in this document. Other key design points in this document include how the North Finding Unit and Rotary Leveling Platform will interact, as well as how the P5 will interact with the personal computer on which its results are displayed.

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P5 North Seeking Gyrocompass
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1. Introduction

The P5 North Seeking Gyrocompass uses MEMS sensor to create an inexpensive and compact alternative to mechanical or fibre optic gyrocompasses that are currently being used in the market. It will be a self-contained unit capable of being powered on an industrial ship, and in the final product release phase will have the ability to interface with the ships onboard navigational system.

The P5 will be broken into two integrated subsystems: the north seeking unit and the self-leveling platform (see figure 1 below). The microcontroller contained within the P5 will determine true North from the information contained within the MEMS sensor. Since determining the rotation of the earth is dependent on the sensor remaining perfectly level, the self-leveling platform will provide periodic rotation using two servo motors and an accelerometer to compensate for the pitch and roll motions of an industrial ship. The P5 prototype will be designed to display a user interface on a PC, and in the final product release phase this user interface will be incorporated into a standalone unit.

The design specifications of the P5 North Seeking Gyrocompass provide details pertaining to the specific computational, physical, mechanical, electrical, safety, and environmental requirements necessary to develop the prototype for the P5.

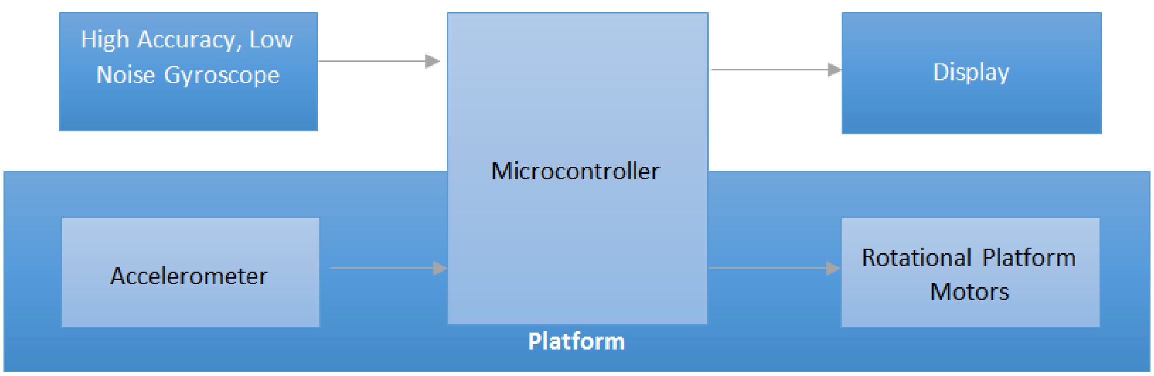


Figure 1. Conceptual Diagram of the P5 North Seeking Gyrocompass.

1.1 Background

Gyrocompasses are a mandatory requirement for industrial ships by the Canadian Coast Guard and numerous other international governing bodies. Due to both their reliability and the fact that they are not affected by electromagnetic interference, they are used to find heading as a replacement for GPS or magnetic compasses.

A MEMS gyroscope is able to provide the same function as the mechanical gyrocompass that the majority of the shipping industry is currently using with the additional advantage of having a lower cost, decreased power consumption, and smaller size. Due to the high usage of MEMS technology in products such as electronics, MEMS gyroscopes are less expensive. MEMS gyroscopes have significantly smaller power consumption than mechanical gyroscopes of comparable size and function. MEMS gyroscopes can also be designed considerably smaller in size and weight than their Mechanical counterparts.

With this justification it was determined that a MEMS gyroscope was superior to a mechanical one and could be developed for industrial use.

2. General Design

The sole purpose of the P5 is to provide heading information, and as such it has been designed as a black box system which users will interact with through a simple application on a personal computer. By limiting user interaction with the system, the potential for human error is limited, and the robustness of the system is increased.

2.1 Overall System

The design of the P5 requires that a user provides input to the system only when the unit is being initiated. This input will be given through a user interface, which will be designed such that initiating the unit is straightforward and could be performed by any sensible user. For the prototype system, the user must manually rotate the P5 360 degrees during initiation in addition to providing input through the user interface. Figure 2 shows the flow of user interaction with the interface during initiation.

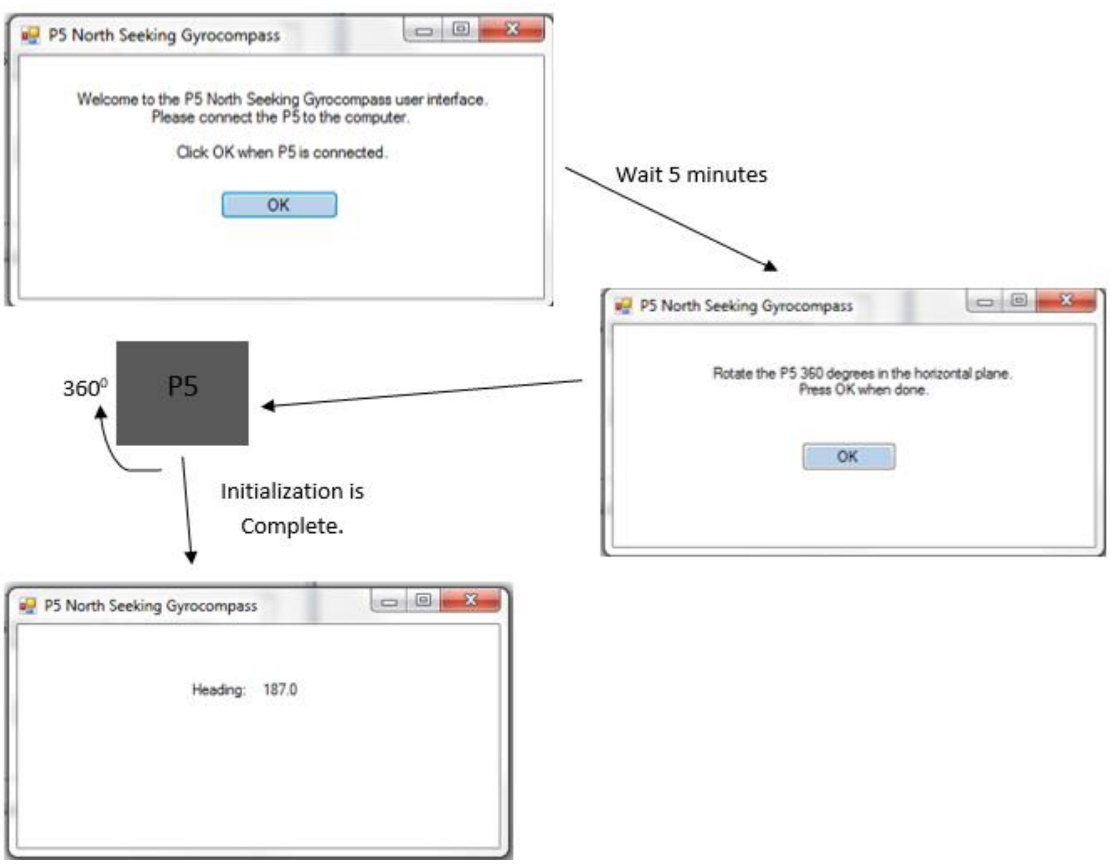


Figure 2. User Interaction with the P5

The total time required for initiation of the P5, starting from being plugged in, will be under 10 minutes. After initiation is complete, the user interface will continue to run and will provide a continuously update heading. The design of the user interface satisfies requirements 4.1.1.I, 4.1.2.I, and 4.1.3.II.

The user interface, pictured in figure 2, will be designed using Windows Forms. The only function of this application is to receive input from the user at initiation, and to display heading. It will perform no calculations relating to north finding or the stabilizing platform - these calculations will be performed on the K64F. Serial communication will be used for communication between the user interface and the K64F.

Requirement 4.1.4.II is met by the overall design of the P5. The gyroscope will be aligned with a predefined reference frame of the system – and this reference frame will be indicated in documentation of the P5. It is assumed that the reference frame of the P5 will be appropriately aligned with the ship on which it is installed.

2.2 North Seeking Unit

Accuracy is a major concern for the design of the North Finding Unit. This is addressed in a variety of ways, ranging from physical means like a protective casing around the entire unit, to carefully selecting the components that will be used in the system.

Environmental sources of error are addressed in part by enclosing the entire P5 unit in a protective case, and by using the Leveling Platform to mitigate pitch and roll during rough sea conditions. Part of the function of the protective case is to address the concern of humidity. Humidity does affect gyroscopes, but can be minimized to a point where it will not affect the system by performing frequent calibrations and using appropriate casing (Patel, 2012).

Selection of a high quality sensor was perhaps the most significant choice made relating to reduction of error; it determines the overall accuracy of the system, as well as other factors such as susceptibility to temperature. The CRS39 has very good error characteristics, and corrects for changes in temperature thereby eliminating error due to temperature in the P5. Details of each gyroscope considered for the P5 are outlined in table 1.

Bias instability and angle random walk are the two main measures of gyroscope accuracy (Freescale Semiconductor, 2015, section 3); both of these measurements are low for the CRS39, so it is suitable for use in a high accuracy system such as the P5. Requirement 4.2.7.II states that the bias instability of the gyroscope used must be lower than the angular rate of rotation of the earth (15 degrees/hour), the CRS39 has a bias instability of 0.3 degrees/ hour so this requirement is met. Specification 4.2.6.II is automatically met by using a gyroscope, as gyroscopes are inherently immune to electromagnetic interference. The combined use of the CRS39, the leveling platform, and protective casing ensure that the North Seeking Unit will function in conditions as might be expected aboard an industrial ship, satisfying requirement 4.2.5.II.

The use of the K64F and Kinetis Design Studio inherently allow for the P5 to be connected to a personal computer for debugging, satisfying requirement 4.2.8.II for the prototype of the P5. The method of allowing a connection between the P5 and a personal computer for debugging purposes will be different in the product release version, but the exact implementation is not known at this time.

The protection of the P5 from environmental factors, combined with computational error corrections, will provide accuracy within 2 degrees. This satisfies requirement [4.2.9.II], which upon being satisfied, automatically fulfils requirement 4.2.10.II. See section 4.2 for further details about computational error correction.

3. MEMS Gyroscope

Three different gyroscopes, the FXAS21002 3 Axis Digital Gyro, the ADXRS150EB and the CRS39 High Performance MEMS Gyro were considered for the P5. Pros and cons of each device are listed in table 1.

Device	Pros	Cons	Chosen
FXAS21002 3 Axis Digital Gyro	Angular rate sensitivity of 0.0625^o/s in ± 2000 ^{o}/s Basic Onboard circuitry to protect against voltages higher than max rated 5000g power shock survivability	High Angle Random Walk(ARW) (0.021 <0.28 dps/rt(Hz) Extremely high noise (noise spectral density of 25 mdps/sqrt(Hz) at 64 Hz bandwidth Integrated Low pass filter	No
ADXRS150EB	High vibration rejection over wide frequency 0.05^o/s sqrt(Hz) Absolute Rate output Small and light (<<0.15cc, <0.5gram)	High Angle Random Walk Noise Temperature sensor output w/o compinsation yields high null Has single pole low pass filter Would require external amplifier to minimize noise complicating circuitry and wiring 5V single supply voltage	No
CRS39 High Performance MEMS Gyro	Low angle Random Walk: typical 0.01 (with abs max of <0.015) Low noise: typical <0.005^o/s rms (abs max 0.01) Low Bias stability: typical 0.08 $^{o/}$h Three temperature sensors for precision thermal compensation Excellent filtering: 2 amplifiers and 3 voltage buffers which filter the signal Regulator for internal regulation of voltages MEMS vibrating ring structure DTG (Dynamically Tuned Gyro) size and performance	-2 ^{o} to 0.7 ^{o} potential misalignment of the gyro	Yes

Table 1. Comparison of Gyroscopes

4. Software Design

When making computational or software related design choices referring to the requirements 8.1.43-44 for the P5 North Seeking Gyrocompass, it is important to remember the requirement for calculations and responses to not be delayed by preventable sources. Designing a unique prototyping board was briefly considered, but then it became clear doing so would not be feasible when considering the short deadline of four months. While the inevitable delays involved in designing and making a third party prototyping board are not specifically known, the cost and benefit analysis of pursuing this option would not be positive. This conclusion came from the cost of lost time spent dealing directly with the onboard microelectronics, to possibly obtain only a minor reduction in delay (not to mention the monetary costs involved). Thus, choosing a development board from a third party majorly depended on the processor limitations, hardware peripherals and software support for our preferred programming language.

4.1 North Finding Calculations

The equation below (Iozan, 2012) will be used to calculate heading based on the output from the gyrocompass.

$$heading = \cos^{-1}\left(\frac{\theta'_{unit}}{\theta'_{earth} * \cos(latitude)}\right)$$

Where θ'_{unit} represents the angular rate of the gyrocompass in radians per second, θ'_{earth} represents the angular rate of the earth in radians per second, and the latitude is in radians

In order to account for noise errors with reference to requirement 8.1.38, a discrete software filter can be applied to data as necessary (low pass filters, averaging the data). Furthermore, the Sensor Fusion Library used as a template allows for the use of Kalman filters to approximate future noise over several measurements.

4.2 Computational Compensation for Removing Rotating Platform

Requirement 4.3.11.II states that the rotary leveling platform will be able to rotate 180^0 in the yaw motion, and requirement 8.1.41.II states that the North Seeking Unit will communicate with the Rotary Leveling Platform for calibration purposes. These requirements will not be implemented in the prototype of the P5 because it was determined that it is possible to replace the function of this feature by using computational methods and requiring the user to manually rotate the P5 once at initiation.

The main purpose of the rotating platform was to aid in correction of bias error in the output of the gyroscope; this would be done by using the rotating platform to rotate the CRS39 180^0

between measurements and using the rules of cosines to eliminate bias error. Bias error will still be corrected for, simply by calculating the bias at initiation, and then subtracting this value from all gyroscope output. Bias variation over temperature will not be a concern in the P5 because bias calculations will be done after the sensor has been allowed time to warm up and reach a constant temperature, at which point this factor will essentially be zero (Silicon Sensing, 2016, Bias Drift).

5. Microcontrollers

In searching for development boards applicable for the project, recurrent themes of more general capabilities of development boards rather than the specializations of other design methods became obvious. However, a prospective discovery was made in a relatively new series of boards developed by Freescale (fully integrated into NXP as of December 2015). From board to support documentation, a choice from the Freescale series evolved into a brighter choice than other boards but still, design choices could not be blindly made. Additional boards considered more greatly than others were the EFM32WG and two Nucleo boards from different series (L476RG, F411RE).

5.1 Processor Limitations

To maintain a simpler learning curve on using the tools necessary to the project, an ARM based controller was decided from the start. Although in the past dsPIC based controllers were more popular, ARM was chosen for the Notos team's experiences in them and general good performance as 32-bit architecture as opposed to dsPIC's long running experience with 8 or 16-bit architectures. Deciding on ARM also allowed for an easier selection in processors involving a floating point unit needed to speed up calculations which narrowed down the selection to Cortex M4's and Cortex M7's. Exploring the capabilities of general Cortex M7's also revealed their specifications far outdid what was needed for our project. Atmel's M7 based microcontrollers provided performances of about 300MHz and the speed of a double floating point unit over a single but a larger price tag as well. In the end, a more modest M4 was chosen since processors rated at around 100MHz using a single floating point unit would be sufficient due to the continuous calculations inherently being simple.

Now turning away from the architectures, the listed max processor frequencies of different boards are placed into Table 2. (All boards included a floating point unit)

Development Board	Max Processor Frequency **(MHz)**
Frdm-K64F	120
Nucleo-F446RE	180
Nucleo-L476RG	80
EFM32WG	48

Table 2. Processor Comparison

The K64F and the two Nucleo boards were enough since continuous leveling orientation and north seeking calculations were estimated at 10-20% of their processing powers. Without the floating point unit, the processors would be burdened to around 60-80% (which actually allowed us to implement both sub-section software on one microcontroller). The EFM32WG was initially investigated due to its ultra-low power consumption with their advanced energy management system allowing micro-ampere usage. Nonetheless, the EFM32WG was given a lower priority in choice because the very low processor frequency rating was undesirable in the case of unforeseen circumstances.

5.2 Hardware Peripherals

The overall system would need access to several different common peripherals used listed in Table 3.

Peripheral	Purpose
Serial Peripheral Interface (SPI)	Data Transfer between externally connected devices
I2C (another serial interface module)	Data Transfer between externally connected devices
Universal Asynchronous Receiver Transmitter	Handle USB communication/Controlling Platform Motors
Pulse Width Modulation (PWM)	Controlling Platform Motors*
Timer	Enacting Timed Sensor Readouts/Control
Direct Memory Access Controller (DMA)	In case of data transfer taking too much processing time

*****Different motors with or without encoders can be controlled by either PWM or UART commands

Table 3. Required Peripherals

Most boards considered in general had these peripherals since they are basic components used in some way in most applications. As a result the K64F, EFM32WG and two Nucleo's still fulfilled the approaches' requirements. (The Nucleo L476RG contains a Quad SPI component along with normal SPI's but other electronics in the North Seeking Unit did not require anything more than normal SPI.) Since this a more general factor, requirement 8.1.42 can be fulfilled by setting the interface modules at their fastest respective clock rates keeping in mind the minimum rates of communicating devices (typically in the microseconds).

5.3 Software Support

The K64F, being a platform developed for sensor applications in mind, included extensive support for the P5 North Seeking Gyrocompass. Among the support features is the Sensor Fusion

Library/Toolbox which provided a foundation and excellent documentation on the concept of sensor fusion. This was intended to have an impact on how to handle sensor devices for the leveling platform sub-section.

The EFM32WG is better designed for low power consumption applications with its energy management system. While this is an appealing trait, it was decided as a minor improvement since the P5 North Seeking Gyrocompass would benefit more from low power consumption in emergency situations. The Nucleo's were included as a general-use development board and so, did not introduce any specific positive or negative details.

Requirement 8.1.39-40 regards the actual integrated development environments (IDE), most IDE's from different M4 microcontroller manufacturers explored were similar allowing changing boards as a possibility. These boards are also compatible with an online development environment by mbed allowing for faster initial development but more difficulty in managing larger projects due to stripped down functionality. With ease of software development being required to assist in fulfilling a four month deadline, the K64F had the advantage in its manufacturer and community support for designers.

6. Platform Design

The self-leveling platform is used to provide a level surface for the MEMS gyroscope in rough sea conditions. As the main selling point of using MEMS technology is the compactness, the self-leveling platform would need to mirror that requirement. Various designs were considered in the development of the platform such as concentric rings, stacked motors, and push rods. The initial approach to the design of the platform was to use concentric rings that would support each succeeding layer. However, it was found that the size would dramatically increase where a 4"x4" platform would require an area of 12"x12" by its outermost ring ("Mechanical - Self-Leveling Platform", 2016). Another flaw in this design is the number of parts required and how the weight would be distributed across two pins in each layer. To simplify the design, the second approach to the self-leveling platform was to stack the servos on top of one another. The design would reduce the number of part down to four servo brackets and the associated base and platform sheets. The base would be 4.5"x4.5" while the height would 3.6". The dimensions and the simplicity of the stacked servo design appealed to the design engineers, but the design was rejected due to the effect of translational momentum being imparted onto the gyroscope causing another source of error. Another avenue that was explored was the possibility of using push rods to compensate for the pitch and roll motions. The platform would be suspended with an axial joint in the centre with two ball joints attached to push rods on the motors underneath the platform. The resolution of the design would increase as a rotation of 80 degrees would appear as a rotation of 15 degrees onto the platform. Despite the increase in resolution, the stability of the design appeared unfavourable as the push rods could possibly impart a force in the x and y axis as rods shift to level the platform.

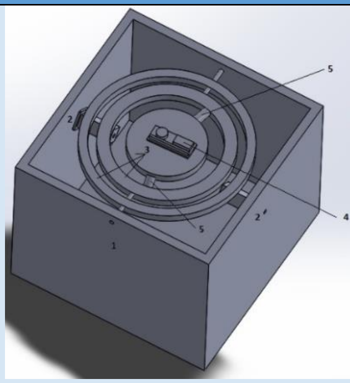
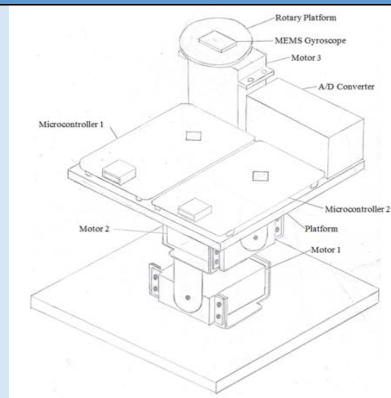
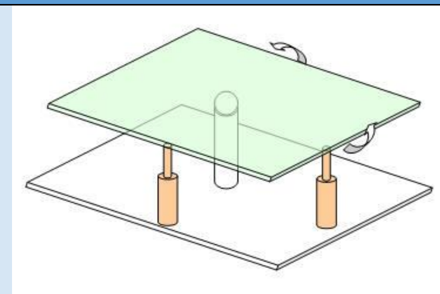
Initial – Concentric Rings	Secondary – Vertical	Tertiary– Push Rods
		 (van Roy, 2016)

Figure 3. 3 Iterations of Platform Design

The final platform design is a fusion of the ideas in the concentric rings design and the stacked motors approach. The roll motor will be attached to a bracket to raise it by 10 mm to allow for rotation of ±15^0. A U-bracket will be connected to the roll motor and to another bracket to provide support. The pitch motor will be attached to the U-bracket and to the platform that will suspend the MEMS Gyroscope at 90^0. The design allows for the direct attachment of the motors to the brackets and reduces height. In order to meet the size constraints of the R191-152-000 container, it was decided to have only the gyroscope mounted on the platform while the other components remain stationary. Requirement 5.3.19.II originally budgets for 500 g of weight on the platform in the case where all of the components are placed onto the platform. However, in this design, only the gyroscope remains, in which the platform is well capable of supporting. The dimensions of the fused platform design was 110 mm by 220 mm with a height of 70 mm thus satisfying requirements 5.3.20.II, 5.3.21.II, 5.3.22.II. Building the platform out of lighter materials such as aluminum, the weight of the fused design is expected to be less than 5 kg as per requirement 5.3.18.II. Due to the reasons outlined in section 4.2, the rotary component of the platform was no longer required and requirement 5.1.14.II was not considered in the later stages of design. The simplistic design of using 3 brackets with 2 motors to achieve a self-leveling platform allows for requirement 5.3.23.II to be fulfilled as the screws are accessible to disassemble the individual components in the case of repair or replacement.

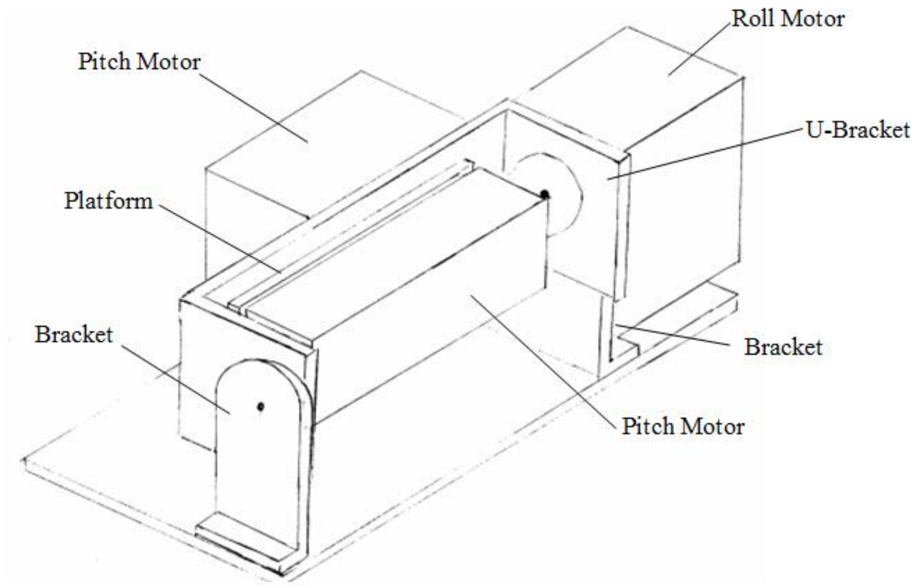


Figure 4. Final Platform Design

6.1 Physical Layout

The R191-152-000 container has dimensions of 150mm x 260 mm x 90mm satisfying requirement 5.1.12.II as all of the components can be packed neatly within the sealed container (Manufacturing, 2016). The main contributors to weight will be the self-leveling platform and the weight of the container. The weight of R191-152-000 is 1.8 kg therefore the P5 is expected to fulfill requirement 5.1.13.II (Manufacturing, 2016). The design of the platform will remain consistent in the prototype and production versions with the possibility of rearranging the components within the container.

6.2 Physical Design of the North Seeking Unit

The form factor of the microcontroller board used is 3.2” by 2.1” or 81mm by 53mm, to fit into the dimensions of the leveling platform to satisfy requirements 5.2.15-17. The microcontroller board is also capable of being screwed down by four different contact points at each corner of the board. External components necessary to the North Seeking Unit will be securely attached currently using right angle connectors but in latter stages will be soldered to be more secure.

ARM – Advanced RISC Machine
IDE – Integrated Development Environment
PWM – Pulse Width Modulation
RISC – Reduced Instruction Set Architecture

SPI – Serial Peripheral Interface
UART – Universal Asynchronous Receiver Transmitter

7. Accelerometer

The use of an accelerometer in the P5 is to measure pitch and roll motions of the ship. In the absence of linear acceleration, accelerometers are able to measure pitch and roll from the effect of gravity on the x-axis and y-axis as it is tilted ("Accelerometers", 2016). Following the decision to use the FRDM-K64F, compatible sensor boards from Freescale Semiconductor were considered taking into account factors such as sensitivity, output noise density and zero-g level offset accuracy. Requirements 7.1.35.II and 7.1.36.II can be easily achieved as all of the sensor boards are able to sense ±2, ±4 and ±8 g worth of acceleration and are 3-axis accelerometers. The following properties are from the datasheets provided by Freescale Semiconductor for their respective accelerometers.

Development Board	Accelerometer	Sensitivity (mg/LSB)	Output Noise Density (µg/√Hz)	Zero-g level offset accuracy post-board mount (mg)	Cost ($)
FRDM-STBC-AGM01	FXOS8700CQ	0.244	99	±30	15.95
FRDM-STBC-SA9500	FRXLC95000CL	0.061	100	±100	31.95
FRDMSTBC-A8471	FXLS8471Q	0.244	99	±30	31.95

Table 4. Accelerometer Comparison

The mechanical specifications for the FXOS8700CQ and FXLS8471Q are identical in nature with the FXOS8700CQ having a lower cost and with the addition of a magnetometer. As seen in table 4, the decision between the FXOS8700CQ and the FRXLC9500CL on the accelerometers alone would be the trade-offs between sensitivity and zero-g level offset. Zero-g level offset is the value that the sensor reads when no acceleration is applied (Ganssle, 2016). As the zero-g level offset accuracy of the FRXLC95000CL is more than three times that of the FXOS8700CQ, the FXOS8700CQ was chosen as the accelerometer will be used to detect the presence of gravity for the calculation of pitch and roll.

However, the FRDM-STBC-AGM01 contains a low noise 3-axis accelerometer as well as a magnetometer and gyroscope. The sensor board has the capability of using the Sensor Fusion

Library to fuse data collected from its various sensors to provide more accurate readings implementing filters such as a low pass filter or indirect Kalman filter. A Kalman filter is a recursive algorithm that multiplies the Gaussian of the predicted and measured results to provide a better estimate (Faragher, 2016). The Sensor Fusion Library uses an indirect Kalman filter to reduce the measurement error quaternions. Factoring in the reduced cost, lower zero-g level offset, and the capabilities of the Sensor Fusion Library, the FRDM-STBC-AGM01 was chosen to be used in the prototype of the P5.

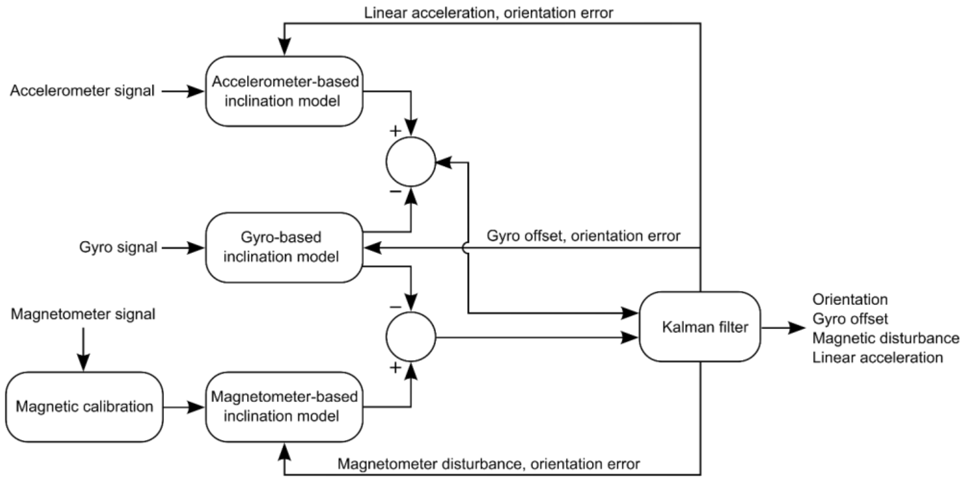


Figure 5. Block Diagram of Sensor Fusion Library's 9 DOF (Freescale Semiconductor)

8. Motors

Motors	Torque	Operating Voltage	Control System	Weight	Cost
Hitec HS-5485HB	0.508 N-m – 0.579 N-m	4.8 V – 6.0 V	Pulse width control	45.0 g	$29.58
Futaba S9451	0.685 N-m – 0.784 N-m	4.8 V – 6.0 V	Digital	56.0 g	$106.15
Dynamixel MX-12W	See paragraph below (0.2 N-m at 12V)	10 V – 14.8 V	Digital Packet	54.6 g	$87.45

Table 5. Comparison of Motors

The table above highlights a few of the motors the team at Notos had considered using for the self-leveling platform. The maximum torque required by the motor selected for the self-leveling platform would be calculated based on the forces the motor controlling the outer U-bracket would need to overcome. As such, the calculations for the torque involved treating all components being acted upon by the motor as one single solid body. Subsequently, the centre of mass of the single body was found to find the mass and distance. Taking the cross product of the mass and distance will yield an approximation of the torque. As stated in requirement 7.1.33.II, the motors require a minimum stall torque of 0.4 N-m. However, after completing the torque calculations on the new platform design, the minimum stall torque required is now 0.0035 N-m. All motors considered satisfy the stall torque requirement of the new platform.

Using the table of motor specifications found above, the team at Notos decided to select the Dynamixel MX-12W for the motor of choice for the self-leveling platform. Three main factors were used to arrive at the conclusion of selecting the MX-12W's. The first major factor revolves around motor performance. With a stall torque requirement of 0.4 N-m, the MX-12W definitely satisfies that criterion. But the precision provided by the MX-12W could not be matched by the other two motors. With an application such as maintaining a constant horizontal alignment, high precision is required for the P5 to operate accurately. The MX-12W provides 4096 steps per revolution, which corresponds to a change in 0.088° per step allowing for precise positional control.

The second major factor was functionality. The MX-12W operates using serial communication, the motor is controlled by packets of information sent from the microcontroller. This type of control system allows for highly accurate and precious control of the motors, allowing for fine tuning the motors to meet the demands of the self-leveling platform. In addition, the MX-12W provides excellent feedback to the user. Not only capable of receiving packets, the motor can send a status packet to the microcontroller indicating any errors observed. As a second layer of feedback, the motor has an alarm used to warn of parameters exceeding defined limits such as heat, speed, and torque. The feedback systems help maintain safe operations of the motors, ensuring the longevity of the P5 North Seeking Gyrocompass.

9. Electrical Design

The system will be powered by what is typically an onboard ship power supply of 12VDC to 24 VDC as per requirement 6.1.24.III. In circumstances where 120AC is available, a simple 12V AC/DC wall power supply can be used to modify the system. Within the North Seeking Gyro Unit a voltage of 12 VDC at 1A is required for the AX-12W and voltage of 5 VDC at 0.5A is required for the FRDM-K64F and the CRS39. The UEI15 (UEI15: Isolated Wide Input Range 15-Watt DC/DC Converters) will be used to ensure a constant DC voltage of 12V into the North Seeking System as per requirement 6.1.vi.III and ensure the motors are powered at a constant 12V as per requirement 6.3.31.I. Since a voltage of 12V is too high for the FRDM-K64F it is necessary to step down voltage to 5V using a V78-500 (V78-500: Non-Isolated Switching Regulator) as per requirement 6.1.25.II. Three MAX1659 low-dropout linear regulators contained within the MAXREFDES4# a 16- bit Analog Front End (AFE) (see Table 6) will provide further current limiting and thermal overload protection, as well as low dropout voltages for the MEMS Gyroscope (Campbell (MAXREFDES#4)) as per requirement 6.2.29.II.

Since noise within the software algorithms are a major source of error and standard voltage sources such as the onboard ship power supply tend to fluctuate at random, a 5V linear regulator will be used to decrease the noise of the ship's power supply prior to its entering the FRDM-K64F as per requirement 6.3.30.III. Upon exiting the FRDM-K64F into the motors, the voltage will need to be stepped up from 3.3V to 5V with a level converter as per requirement 6.3.31.I. This will allow data transfer of leveling platform algorithms to be communicated to the servo motors.

In order to further ensure all electronics are protected, the wiring will maintain a grounded contact to one of the internal screws that holds the baseplate to the box containing the North Seeking Gyro Unit as per requirement 6.1.26.II. Since optimizing for smaller size is extremely important, wiring will be done with W2628R-ND, a flexible and durable wire that will allow the components to be easier to maneuver with respect to each other, contributing to a smaller overall size for the Gyro Unit as per requirement 6.1.27.II.

A/D Convertor	Pros	Cons	Chosen for Project
MAXREFDES#4 ***ANALOG FRONT END (AFE)***	High accuracy Linear regulators to protect gyro 16 bit (oversampling occurs at this rate) 0.2V to 4.096V input range (positive voltage range—simplified algorithms)	External (more wiring as testing and developing) Less ability to modify at the design stage since already a development board	Yes
FRDM -K64F (ADC)	High speed 16 bit with configurable resolution Operates on separate micro USB for data transfer	Less optimization Increased noise Increased complexity of algorithms Increased wiring	No

Table 6. A/D Convertor Onboard Microcontroller vs. Analog Front End

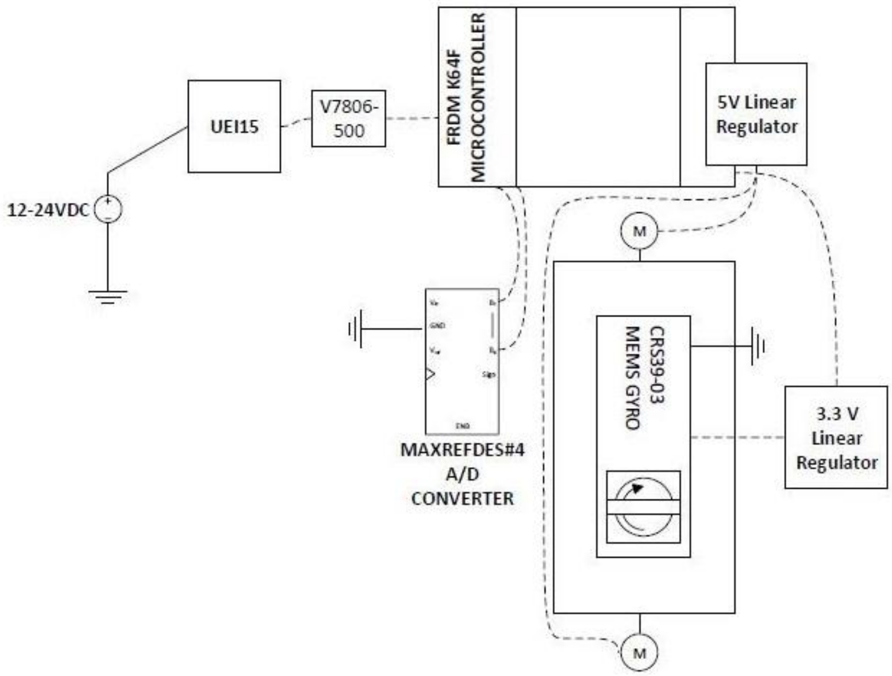


Figure 6: Components and wiring

**Note I: Re: Requirement 6.2.28.II Two microcontrollers were originally planned for the development phase of the P5 however implementation of both the Platform and North Seeking Subsystems algorithms on one microcontroller was determined to be higher priority for this phase of development. In consequence the subsystems do not need to be connected as they are already integrated. For further notes on calibration see section 4.2.*

Note II: RE 16- bit AFE. Given the noise that has been noticed in testing, and the low voltage in the signal it may be necessary to upgrade to a 24 bit analog to digital convertor. Further testing is necessary at this stage with the 16-bit convertor to determine whether there is a need for oversampling and filtering.

10. Design for Safety

Regarding 9.2.49, the P5 North Seeking Gyrocompass is inherently a safe piece of equipment to operate due to the decision to use microelectronics and a few motors controlling a small platform. The power levels used by the microelectronics (3.3V-5V at milliamps) would not be able to harm an operator. The only potential danger of light injury lies in the leveling platform sub-section. The leveling platform sub-section contains servo motors used to control the movement of the small and durable base but will not be able to detect unauthorized objects within its range of motion. However, the P5 North Seeking Gyrocompass is designed with such small physical dimensions to also be placed within a potential IP67 protective casing (9.2.xvi). The protective casing will prevent interferences such as water to human touch from reaching the internal systems. This is one of the design factors created to prevent operators utilizing the device from interacting with the internal components and hurting themselves. Future design versions can include sensors detecting whether or not the casing is opened and possibly pause the device until it is closed.

11. Environmental Considerations

The P5 North Seeking Gyrocompass is designed for use onboard marine vessels. Due to the nature of the usage, the P5 must be able to withstand a certain threshold of environmental conditions commonly found aboard a marine vessel in order to properly meet the demands. For these purposes, considerations will be made in regards to angle of tilt, variances in temperature and protection from moisture.

The team at Notos had agreed upon the following conditions to be met in order to satisfy the requirements of successful operation in real time while withstanding ship movement in rough sea conditions. Rough sea conditions will be defined as vibrations and motions of the marine vessel causing the vessel to tilt up to 15°. Such an angle was chosen as any larger value would result in major disturbances to the orientation of the vessel itself. In addition to the amount of motion, the P5 must be able to withstand any reasonable variances in temperature and amounts of moisture as would be expected while aboard a marine vessel.

The issue of tilting of the P5 will be addressed using the self-leveling platform designed directly into the P5. The sole purpose of the self-leveling platform is to provide a constant horizontal position of the MEMS gyroscope used in the P5. The platform will counteract any motions of the marine vessel, continuously adjusting motions in the roll and pitch direction to compensate any tilting. This component will ensure a constant position under the tilting motion of up to 15°. The compensated motion will provide the gyroscope with the orientation required to allow for the most accurate measurements. This design satisfies requirements 9.1.47.II and 9.1.48.II.

The P5 will be contained within a R191-152-000 enclosure, which has an Ingress Protection (IP) rating of 67. IP rating provides two pieces of information used to describe the protection of certain enclosures. The first digit indicates protection from intrusion, while the second digit indicates protection from moisture (Hemmingway, 2016). In the case IP67, the 6 indicates the enclosure is dust tight, and the 7 indicates the enclosure is protected from immersion in liquids from 15cm up to 1m ("IP - Ingress Protection Rating", 2016). The team at Notos arrived at the choice of the R191-152-000 model due its ability to satisfy the requirements stated, in addition to the size of the enclosure. By enclosing the P5 in the R191-152-000 enclosure, the P5 is protected from any reasonable fluctuations in both temperature and moisture.

12. Test Plan
12.1 System Test Approach

In the proof-of-concept phase and a portion of the prototyping phases, most testing approaches will be more focused on requirements which may not be developed with the release product copy in mind. While in the more design and technical extensive stages of product development, more detailed or lower level testing approaches will be undertaken.

For more applicable results, rather than testing the entire system altogether in one method, the system will first be tested in its appropriate sub sections. Once completed, sub sections will be integrated together and testing would continue with the full unit. The system has been divided into the two sub sections regarding the North Seeking Unit and the Self-Leveling Platform.

12.2 North Seeking Unit Testing Approach

Besides being conscious of the dimensions of the component, the approach taken for the North Seeking Unit will mostly involve making sure most electrical connections are secure, reliable and durable. These electrical requirements will be tested and calibrated during each rendition of the prototyping phase, and so will be in constant check.

1. DC supply voltage powering the unit will be adjusted to determine that the P5 North Seeking Unit can sustain inconsistencies in power
2. Input and output lines will be checked with a multimeter to ensure the voltage regulators are working correctly and that components are receiving the correct stepped up or down voltage.
3. The platform and lines will also be tested for faulty connections before a complete boot up is started.

Another set of requirements to be fulfilled during testing is the actual functionality of the device in receiving and transmitting appropriate data accurately. This means software testing procedures for error calculations, filter functions and conversion equations may be necessary if glitch possibilities are present in these areas. A survivability test will also be utilized to ensure the direction seeking components are able to go through constant use without breakdown or data deterioration over long periods of time.

12.3 Rotary Leveling Platform Testing Approach

Again, being conscious of the dimensions of the platform, the Self-Leveling Platform will be approached mostly from a mechanical perspective. Testing will take place regarding the freedom of movement such that other electrical or mechanical parts would not impede movement. The angle of pitch and roll motions will be experimented to confirm the platform is able to support motion with as little irregularities as possible. The platform will also undergo rigorous motion testing as to not be a source of error for the North Seeking Unit. As with the North Seeking Unit, a survivability test will also take place to ensure important mechanical parts will not break during periods of stress.

Other sets of requirements to be tested for the Rotary Leveling Platform are associated with the computational and electrical aspects. Due to the Self-Leveling Platform being used to perform corrections such that the mounted North Seeking Unit remains purely horizontal, later on investigations will be done to correlate small delays with microcontroller processor speed. Furthermore, observations on electrical connections will be made to avoid damaging the system with incorrect or incapable connections. The following tests will be implemented to ensure that the self-leveling platform provides a stable surface without any tremors. Several tests will be conducted testing the platform's ability to maintain a steady state at rest and in the midst of movement.

1) Placing the self-leveling platform parallel to the horizontal plane, the platform will be able to maintain a steady position that is $\pm0.5^{\circ}$ in pitch and roll axes.
2) Maintaining a static position of 15° to the horizontal plane in either pitch or roll, the platform will be able to shift 15° and maintain a steady position that is $\pm0.5^{\circ}$ in the pitch and roll axes.
3) Mimicking the movements of an industrial ship, the platform will be gradually tilted in either pitch and roll axes where the platform is expected to provide a smooth transition while leveling the platform. Regardless of sudden movement, the platform is expected to be able to compensate and continue to provide a level surface for the MEMS gyro.
4) Similar to test 3), the platform will be gradually tilted, but simultaneously in both pitch and roll axes. The self-leveling platform is expected to provide a level surface of $\pm0.5^{\circ}$ to the horizontal plane regardless of movement.

12.4 Full System Approach

The approach taken for the overall system will involve running both subsystems in conjunction to ensure safety of operation during normal and high risk sea conditions. The full system will undergo vast changes in all six translational and rotational movements a sea vessel may experience. During these conditions, the full system must survive an endurance test to imitate long sea journeys with rough conditions. As well, later releases of the full system will be subject to quick changes in temperature and humidity to test the lifespan of electrical and mechanical components.

The overall system will also be subject to tests on its electrical aspects regarding power connections and the self-sustaining portions of the equipment. Tests will be completed to accurately correspond system power consumption with main power sources from the vessel. Further tests will be instituted to examine system response in case of main power supply overload or failure.

Once the subsystems and the full system have been properly released from previous testing stages, a mock run for heading find will be completed by the system. The system will then complete the following general steps:

- Boot up utilizing default settings for minimal user input
- Self-Leveling Platform will perform full 180^0 turns in both directions as well as 90^0 pitch and roll movements then return to normal horizontal position
- North Seeking Unit and Self-Leveling Platform activate calibration mode in to begin accurate heading finder
- North Seeking Unit will after calibration time will relay to operator appropriate data

In each of these steps, diagnostic data regarding calculations, run times and other useful information for tuning the overall system including subsystems will be relayed.

13. Conclusion

The development of the P5 North Seeking Gyrocompass prototype revolved around meeting the functional requirements agreed upon by the members of Notos. As the functional specification tries to answer "What" to meet, the design specification tries to answer "How" to meet.
The intention of the P5 North Seeking Gyrocompass is to be used aboard industrial ships for navigational purposes. As such, many factors were taken into consideration in order to provide accurate, reliable measurements. Starting with the sensor, the choice of using the CRS39, was based upon selecting one of a high grade and excellent specifications in order to meet the accuracy requirements defined. The software computations used in the north seeking carefully took into consideration of improving accuracy by implementing software filters to reduce noise.

The team at Notos decided upon using the K64F microcontroller for the self-leveling platform due to its functionality and familiarity. Using the sensor fusion library as a building block, the self-leveling platform team gained great insight by the documentation provided. Once the decision was reached regarding the microcontroller, the choice of accelerometer followed quite naturally. In addition to meeting the acceleration measurement requirements, the AGM01 was chosen for its lower cost and compatibility with the sensor fusion library.

The functional requirements surrounding the self-leveling platform required sensitive accelerometers and smooth, precise motors. The decision to use the MX-12W motors was based upon the need for high precision motors that provided continuous motion. To address the voltage requirements of the microcontroller and the motors, DC/DC converters were used to ensure each component received the correct amount of voltage. Furthermore, to reduce noise levels, a linear regulator is used to reduce the noise of the power entering the microcontroller.

To address environmental and safety concerns of the P5, the team at Notos decided upon using an enclosure with IP67 rating. The enclosure will provide protection against tampering and excess moisture during normal usage aboard a marine vessel.

Using the functional specifications as a checklist, the design specification has been composed to guide in the implementation of the P5. The test plan provided will be used to assess the success of the P5 North Seeking Gyrocompass against the specified functional deliverables.

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Appendix I: Product Release Requirements

General Requirements

The general requirements for the product release version of the P5 all relate to the fact that the product release device will be a standalone unit. Exact details of how this will be implemented are not know at this point, but the general scheme for making this change will be to replace the user interface that currently runs on a personal computer with an interface on an LCD screen, and use buttons for controls. The interface that is displayed on the LCD screen will include necessary error messages. This interface will be controlled by the same microcontroller that does north finding calculations. The system described above will satisfy requirements [4.1.i.III. 4.1.ii.III and 4.1.iii.III]. The method for interfacing the P5 with other navigational devices, as is necessitated by requirement [4.1.iv.III] has not been decided at this time.

Software Design

Another advantage realized in using a Freescale device was discovered when Freescale was fully merged into NXP. This would potentially allow for future product revisions to contain an NXP processor with the support of the former Freescale sensor fusion experts. Also with the specific sensor software support, different calibration setting implementations were possible without adding substantial differences in program flow (8.1.xiv).

Electrical Requirements

Complete protection against inconsistencies in power supplies voltages and excessive currents was originally planned to be postponed until the Final Product Release as per requirement 6.1.vi.III & 6.1.vii.III. It was theorized in earlier proposal phases of this project that this could be carried out on a component by component basis in the prototype phase. However, as the model for P5 North Seeking Gyro Unit prototype began to take develop it became evident that protection against inconsistencies in power and an ability to operate under conditions where these inconsistencies occur was crucial to the function and protection of the MEMS itself. It was also determined during the prototype phase that the Unit's ability to interface with an onboard power supply was easier to implement initially and formulate the system around as per requirement 6.1.ix.III. The self-containment of the unit was also determined to be higher priority and moved to the prototype phase, this containment will protect wires from environmental conditions as per requirement 6.2.x.III.

For the final product release the P5 will be capable of sustaining itself in the event of a main power supply failure using the ships UPS backup system as per requirement 6.1.viii.III.

Physical Requirements

After extensively exploring various platform designs, the P5 will retain a similar model in the product release version. The final design minimizes the size of the overall platform while allowing for precise control of pitch and roll motions. One change to the brackets that support the platform would be to add ball bearings to allow for a longer lifetime of the self-leveling platform. The prototype model uses Delrin which has a low coefficient of friction, but after several years of use, will eventually degrade. Replacing the Delrin joints with ball bearings will remove the concern for degradation of performance.