**Letter of Transmittal**

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Date: 8/03/13

Dr. Andrew Rawicz
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Dear Dr. Rawicz,

Attached is the Design Specification of the Dynamic Positioning Control System (DPS) being developed by Titanic Positioning. It was written to ensure that the product is compatible with user's need and to clarify the design procedure taken by the company. This document contains specific information about the requirements of the product, along with information about how the product will be constructed. This document will also specify, in detail, both hardware and software aspects of the design, including details about accuracy of each component, and the control system design procedure. A practical test plan will also be provided for further clarification.

Should you have any questions or concerns please contact me at bkh4@sfu.ca. Thank you for your time.

Regards,

Bengt Haunerland
Chief Executive Officer
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# ENSC 440 Design Specification Dynamic Positioning Control System

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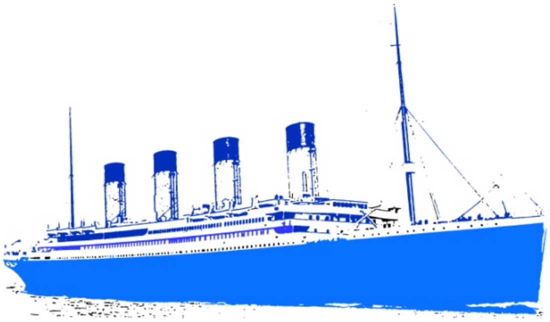

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# Abstract

Titanic Positioning is developing a proof-of concept Dynamic Positioning System (DPS) on a test boat, which will allow for automatic station keeping with minimum human involvement. Automatic Heading Control will be achieved using several components and sensors, and an embedded computer will be used to communicate with the components and run the control algorithm.

This document provides a step by step procedure of how the product will be constructed and tested. A detailed design approach will be provided both in terms of software and hardware, along with the specifications of the controller. This Document elaborates on the functional specification, *Functional Specification Dynamic Positioning Control System* and describes the design methodology that will be used in order to maintain the standards outlined in the functional specification.

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## III. Glossary

**Anemometer** - Wind speed/direction sensor
**Automatic Position Control** - (use keyboard to set desired position)
**Manual Control** - (system is turned off)
**Manual Position Control** - (use joystick to adjust position)

## IV. Acronyms

**ABS** - American Bureau of Shipping
**ANSI -** American National Standards Institutes
**DP -** Dynamic Positioning
**DPS** - Dynamic Positioning System
**DPS-0** - Is defined as a DPS that has a central manual position control and automatic heading control system.
**DPS-1** - Is defined as a DPS that has a central automatic and control and heading system. It also has a manual positioning control.
**GNSS** - Global Navigation Satellite System
**GPS** - Global Positioning System
**HMI** - Human-Machine Interface
**MRU** - Motion Reference Unit
**NMEA** - National Marine Engineering Association
**OS** - Operating System
**SFU** - Simon Fraser University
**PID**- Proportional Integral Derivative

# 1. Introduction

Marine vessels are sometimes required to maintain a heading or a position in situations where anchoring is difficult or impractical. An automated method of maintaining a heading or position is called Dynamic Positioning. Dynamic Positioning is prevalent in the oil industry, where large transport ships dock at offshore oil platforms. The vessels are required to steadily maintain precise coordinates for hours while cargo is transferred. The position of the vessels must be held constant despite exterior forces, such as wind, waves, and tidal pull. This must be reliably done to ensure the safety of the workers on the rig and the ship, and that no product is spilled in the process. [1]

A Dynamic Positioning System (DPS) is a control network that uses the ship's thrusters to adjust and maintain the ship's position according to feedback input from multiple sensors. The ship's location is adjusted and maintained by the DPS controller, which makes a calculation based on the current location of the ship using a GPS, and sensor information gathered from wind and water current data.

The purpose of the project is to implement a DPS on a 10-meter-long boat. The boat will maintain position and heading against external forces, such as the current in the Fraser River. The system will be expandable, and with the addition of further software, will be able to implement full dynamic positioning. The proposed requirements for the DPS are defined in this Design Specification.

## 1.1 Scope

This document describes the Design Specifications for the DPS-0, in compliance with the functional requirements from *Functional Specification Dynamic Positioning Control System*. This will include explaining the technical specificities of how Manual Position Control and Automatic Heading Control will be achieved by interfacing with a GPS, Motion Reference Unit (MRU), Anemometer, and a user interface.

## 1.2 Audience

This Design Specification is written for the all members of Titanic Positioning and the members of Think Sensor Research who are involved in the project. The document shall be used as a reference for designing and building in order to ensure that all functional and design requirements are met. The document will also be used during installation and testing to ensure that the final system is properly implemented.

## 1.3 Background

The DPS will use a GPS, MRU, and Anemometer to determine the present location of the boat. The desired location will be set by the user using a joystick. The control algorithm will be contained on an embedded computer and motor controller. The DPS will control two outboard stern thrusters and a bow maneuvering thruster to move the boat to the desired position and heading. **Error! Reference source not found.** shows a diagram of the proof-of-concept system.

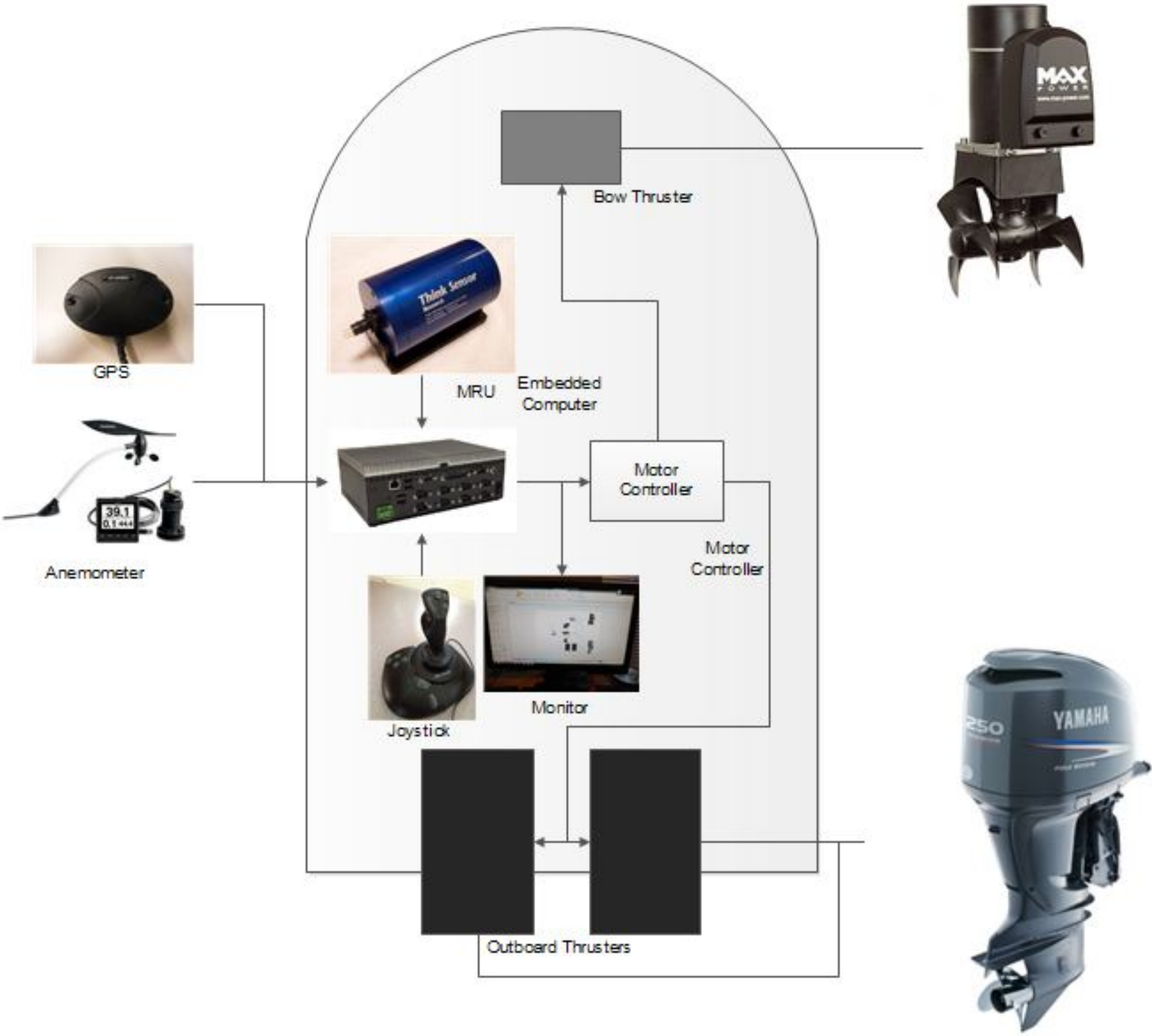

**Figure 1.1: Physical components of DPS**

Figure 1.2 below shows a boat with all the directions of motion that the boat can be moved in from wave and wind forces. In dynamic positioning, surge, sway, and yaw are relevant, while heave, pitch, and roll forces can be ignored because they will not affect the bow-stern orientation of the boat or the position coordinates. [3]

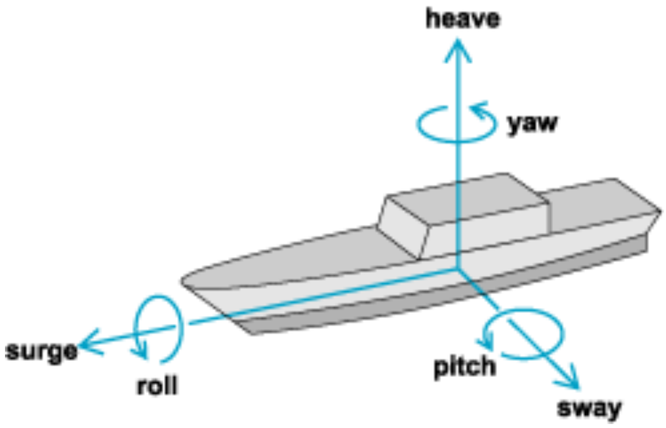

**Figure 1.2: Shows a boat with the components of motion [4]**

## 2. Overall DPS Design

There are many different methods of control, shown below in Table 2.1, that can appear in a DPS. **Error! Reference source not found.** explains the difference between a DPS-0 and a DPS-1.

| | |
|---|---|
| Manual Control | Human operator controls ship without DPS. |
| Manual Position Control | Human operator uses joystick to manually set coordinate destination for DPS. |
| Automatic Position Control | GPS coordinates are set with keyboard from a distance and have automatic fine tune control. |
| Automatic Heading Control | DPS maintains the direction automatically based on data from the MRU. |

**Table 2.1: Different features of a Dynamic Positioning System [2]**

| | |
|---|---|
| DPS-0 | DPS-0 has Manual Position Control and Automatic Heading Control. Initial desired position is set by GPS/MRU. |
| DPS-1 | DPS-1 has Automatic Position Control and Automatic Heading Control. Initial desired position is set by user with keyboard. DPS-1 is capable of using Manual Position Control, if required. |

**Table 2.2: Explains the difference between DPS-0 and DPS-1 [2]**

## 2.1 Design Approach

Table 2.3 below shows the advantages of designing the DPS for a test boat on the Fraser River. There are some disadvantages such as cost and different thruster configuration from targeted vessel. The overall benefits of a real ocean environment, proper scalability, and integrating with boat hardware outweigh the disadvantages.

| | **Scale Model** | **Test Boat** |
|---|---|---|
| **Environmental conditions** | Hard to simulate wind, wave and current forces in a lab. | River wind, current, wave forces are similar to ocean environment |
| **Scale dynamics** | Non linear scaling will be difficult to map onto a vessel | comparable water dynamics to final product conditions |
| **Existing Hardware** | No pre-existing hardware or systems | Existing hardware on test boat |
| **Thruster configuration** | Same as final product | Different from target final product. |
| **Financial cost** | Cost of materials only ($3870) | cost of material and boat usage ($4870) |

**Table 2.3: comparing a scale model to a test boat. See appendix A for more detailed cost analysis.**

Figure 2.1 below shows the data streams in the final proof-of-concept system. All the inputs are sent to the embedded computer along serial lines (RS-232) or USB ports. The controller is contained on the embedded computer and all calculations will be performed on the embedded computer using C/C++ functions. The controller interfaces with the monitor and the motor controller unit, which is used to control the direction and throttle of all the motors on the boat.

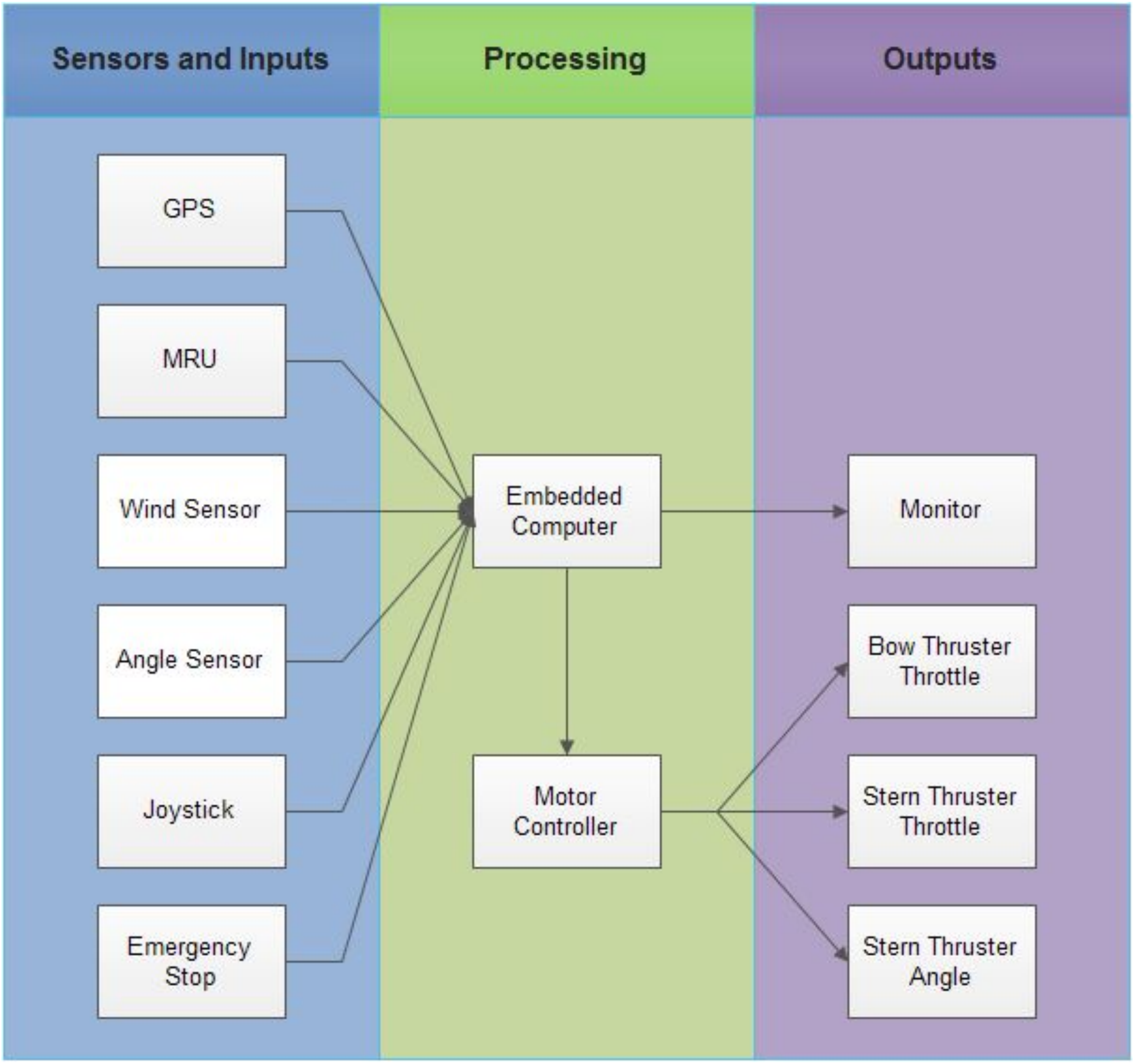

**Figure 2.1: Flowchart showing data streams for DPS-0**

### 2.2 Design Components

This section will deal with the various components that will be used in the design of the DPS. The design components are split up into the following sections: sensors, serial communications, embedded computer, motor controller, motors, wiring, and display computer.

#### 2.2.1 Sensors and Inputs

This section lists the sensors that are used in the project. The following sensors are required to implement a DPS-0: GPS, MRU, joystick, and emergency-stop-button. The GPS, MRU, and anemometer are used for collecting data. The joystick is used for controlling the desired location and heading. The emergency stop is used for safety to manually stop the DPS. Table 2.4, below shows the sensors and inputs that will be used in the proof-of-concept design.

| **Sensors and Inputs** | **Product Number** | **Specifications** | **Justification** |
|---|---|---|---|
| GPS | MD 762-1009-07A<br>SR 0404-14391-0001 | Serial RS-232, Average GSP resolution is 1 m | Re-used, marine grade |
| MRU [5] | TSR-100 | Anodized aluminium, 7-36 Vdc power, 1cm heave resolution, 5% heave accuracy, +/- 0.5 degree orientation accuracy, serial RS-232 | Produced by Think Sensor research, has a compass and measures heavy, pitch, roll, and yaw. |
| Anemometer [6] | Garmin GWS 10 | Wind speed and wind angle measurements. Wind speed/angle filtering included | has built in filter so that measurements can be take mean or average wind speed |
| Joystick | X03-57540 | Microsoft Sidewinder. USB input, linux compatible | Re-used, has z-axis rotation |

| | | | |
|---|---|---|---|
| Emergency Stop button [7] | Game Switch - SPDT Square Red Lens, On-(On), Illuminated | 5A/125VAC, Plastic pushbutton assembly, | Light gives feedback and is red colour is obvious for stop |

**Table 2.4: Products used for proof-of-concept**

### 2.2.2 Serial Communication

This section discusses serial communication with the Linux Operating System that will be used for the DPS. Computer device interface involves asynchronous communication ensuing the RS-232 protocol standard. Information data is exchanged as character strings with each character encoded as ASCII. The each character is represented with one byte of binary signals and the transmission format is illustrated in Figure 2.2. For more information on serial communication reference Appendix B.

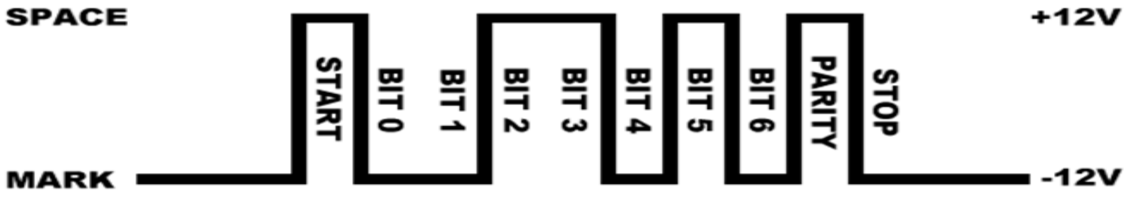

**Figure 2.2: Serial bit characterization**

### 2.2.3 Embedded Computer

The development board will be used until the embedded CCS computer arrives. One advantage of both of these computers is that they are fanless and have solid state drives, which makes them durable enough to deal with the environmental conditions. Table 2.5 below, shows a comparison between the development board and the embedded computer.

| | **Development board (Zotac Z-box add product name)** | **Embedded computer CCS Fanless Marine CPU [8]** |
|---|---|---|
| **Processor** | AMD E-350/D APU, dual-core, 1.6 | Intel Atom dual-core, D2550, |

| | | |
|---|---|---|
| | GHz | 1.86 GHz |
| **Chipset** | AMD M1 Chipset | Intel NM10 Express Chipset |
| **Serial ports** | 1 RS-422 | 10 RS-232 |
| **USB ports** | 3 USB 2.0, 2 USB 3.0 | 5 USB 2.0 |
| **Memory** | 4 GB | 4 GB |
| **Power required** | DC 19 V | 12-36 Vdc |

**Table 2.5: Comparison between the development board and the embedded computer**

### 2.2.4 Motor Control

A motor controller is essential to communicate with the thrusters because the SFU test boat has a hydraulic steering and cable throttle control. An electric autopilot control and servo motor control for the throttle will be used to interface with the control system. These controls will be supplied by Think Sensor Research, since adding the autopilot and servo motors are outside of the scope of the project. Titanic Positioning will help install the motor controls. The large vessels, which the DPS is designed for, already have electric motor controls with which our DPS will be able to interface.

### 2.2.5 Thrusters

The SFU test boat has 3 built-in thrusters: a bow thruster and two stern outboard thrusters. Table 2.6, below shows the specification of the thrusters on the test boat. The bow thruster is a tunnel thruster, which can only spin clockwise or counter clockwise, and has no speed control on it. The left and right stern thrusters can swivel, and can run in forward or reverse. The two stern thrusters can only be rotated together. The outboard stern thrusters are more powerful and can move the boat forwards, backwards, left, and right. The bow thruster can only spin the boat left or right, and at one speed.

|  | **Part number** | **Specifications** |
|---|---|---|
| **Bow Thruster [9]** | MPSPC512 80 DUO 12V | tunnel diameter 185 cm, 15 kg, 4.79 kW, 6.4 hp, single speed, bidirectional blades |
| **Left Stern Thruster [10]** | 2006 Yamaha LF250TXR | 4 stroke gasoline engine, 250 hp, min cold cranking amps: 512 A, bidirectional blades |
| **Right Stern Thruster [10]** | 2006 Yamaha F250TXR | 4 stroke gasoline engine, 250 hp, min cold cranking amps: 512 A, bidirectional blades |

**Table 2.6: Specifications of the bow and stern thrusters**

### 2.2.6 Power Supply

Both the GPS and MRU require a DC power source, supplying between 8V and 30V. A Panasonic Valve Regulated Lead-Acid 12V battery will be used for initial testing. When the system is installed on the test boat, the test boat's onboard power supply will be used instead.

### 2.2.7 Wiring [11]

Standard 20-gauge marine cable RS-232 will be used to connect all the sensors, inputs, and outputs to the embedded computer.

### 2.2.8 Display Computer

In the proof-of-concept, the embedded computer also functions as the display computer, and will send visual information to the user's monitor. In the production version, the graphics processing will be handled by a separate, dedicated computer.

# 3. Control System Design

## 3.1 Controller

The controller will be implemented with a conventional Proportional Integral Derivative (PID) Controller. A PID controller was chosen because it reduces rise time, overshoot, and steady state errors. Table 3.1 below shows the important components of the DPS control system. Individual wind gusts have too high a frequency to be compensated for, and only the mean wind forces are compensated by the wind feedforward controller. The PID controller will be in cascade with a low pass filter to remove high frequency wave oscillations, since the thrusters cannot respond fast enough to compensate for it. [3]

## 3.2 Control System Components

Table 3.1 below shows the purpose of each control system component that will be programmed.

| **Control System** | **Purpose** |
|---|---|
| Integral Action | Compensate for wave drifts and slowly changing ocean current forces |
| Wind Feedforward | Compensate for mean wind forces |
| Optimal Thruster Setpoints | Aligns thrusters to direct boat to compensate for environmental forces and moments such as c |
| Low Pass Filter | remove high frequency wind and ocean wave oscillations |
| State Estimation | Noise filtering and estimations of unmeasured states |

**Table 3.1: DP control system components**

## 3.3 PID Design

The goal of the PID controller is to process the signals sent in from the sensors, and output a fast and stable response. The proportional (P) component reduces rise time of the response, so the DPS reaches its desired position faster. The integrator (I) component reduces steady state error caused by slowly varying ocean currents and wave drifts. The differentiator (D) component reduces overshoot so that the system thrusters do not overcompensate.

Figure 3.1 shows the control system that will be used on the proof-of-concept. The controller is made up of several different components including a PID component, a wind feedforward system, wave filtering, state estimators, and thrust allocation. The wind feedforward system takes in wind speed and direction from an anemometer and then compensates for the mean wind. The wave filtering filters out high frequency wave components from both wind and ocean waves, since the boat cannot respond fast enough to compensate for high frequency ocean waves and wind gusts. The state estimator is used to estimate unmeasured states such as linear and angular velocities. The state estimator is implemented using a Kalman filter. The last part of the control algorithm is the thrust allocation which will tell the two stern thrusters which way to turn and what speed to use. It will also tell the bow thruster when to turn on and whether to spin clockwise or counter clockwise. The output will move the thrusters and provide the new position and heading, which is measured by the GPS and MRU. The GPS and MRU provide feedback into the system and are compared to the desired input position from the joystick. The entire controller system will be contained on the embedded computer. [3]

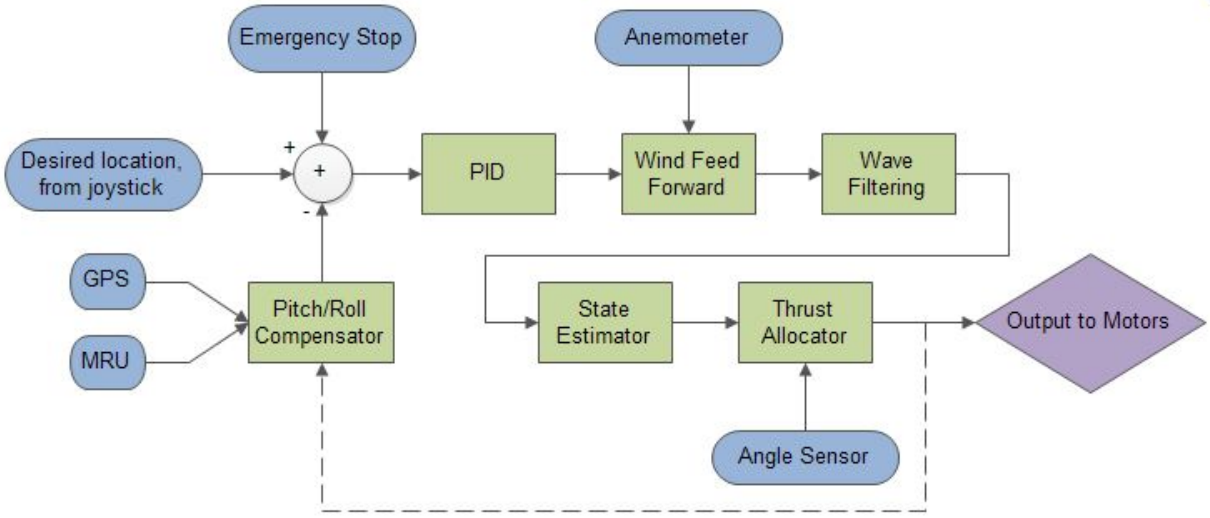

**Figure 3.1: Flowchart of the DPS controller. The colour-coding matches Figure 2.1**

### 3.4 Programming Language

The program will be written in C++ because of it's prevalence in industry and usability, which will reduce time during maintenance and troubleshooting. C programs can be used as well. Low level languages were avoided because it makes it difficult to expand the DPS to higher levels of positioning. Low level languages are also difficult to debug and are very time consuming.

## 4. Process details

During the course of the term, Titanic Positioning will complete a DPS-0 proof-of-concept design. The project will be expandable for prototype and production purposes, as well as higher classes of DPS. Table 4.1 shows the differences between the different stages of design.

The proof-of-concept design will use a development board with a separate USB to serial adapter. The USB to serial adapter will be enclosed in a metal container, with the wires temporarily secured.

| | **Proof-of-Concept** | **Prototype** | **Production** |
|---|---|---|---|
| **DPS-0** | Off-the-shelf components | Off-the-shelf components | Off-the-shelf components |
| **DPS-0** | Development board with external additional serial ports as the control computer | Embedded computer with enclosed serial ports as the control computer | Embedded computer with enclosed serial ports as the control computer |
| **DPS-0** | Temporary secured wires | Permanently secured wires | Permanently secured wires |
| **DPS-0** | Reused marine GPS | New robust marine GPS | New robust marine GPS |
| **DPS-0** | MRU | MRU | MRU |
| **DPS-0** | Display monitor, keyboard, and joystick controlled by development board. | Display, keyboard, and joystick controlled by dedicated computer. | Display computer will have a built in trackball and keyboard. |
| **DPS-0** | Anemometers | Anemometers | Anemometers |
| **DPS-1** | | Addition software for Automatic Position | Addition software for Automatic Position |

| | | | |
|---|---|---|---|
| | | Control | Control |
| **DPS-1** | | Water current sensor | Water current sensor |
| **DPS-1** | | | Fanning lasers on dock |
| **DPS-1** | | | North Seeking Gyroscope |

**Table 4.1: Comparison of proof-of-concept, prototype, and production**

## 5. Test Plan

Titanic Positioning will test the system throughout the entire development phase. Table 5.1 below shows the order that components will be tested.

| | **Test Plan** |
|---|---|
| 1. | Test individual sensors to ensure the data being captured is correct |
| 2. | Test the control system with all sensors connected to ensure that the sensors are properly communicating with the controller and with each other |
| 3. | Test control system to ensure it communicates to the thrusters properly and to the interfaces on the motors |
| 4. | Test the DPS on the boat |

**Table 5.1: Order in which components and code will be tested**

The following table outlines the required testing that will be done at SFU in the lab, and the expected results.

| **Component/sensor to be tested** | **Test Procedure** | **Results/Comments** |
|---|---|---|

| | | |
|---|---|---|
| **MRU** | Tilting and measuring output signal | Ensure the MRU communicates with the embedded computer and that the reading is accurate |
| **GPS** | Develop a mobile system and move around campus | Ensure location accuracy and communicates with embedded computer |
| **Anemometer** | Simulating wind using a fan | Ensure the accuracy of wind direction and communicates with embedded computer |
| **Motor Control** | Simulating maneuvers | Ensure proper outputs are being communicated to and from the embedded computer |
| **Shutoff Command (switch)** | Pushing manually | Verify complete release of control to manual mode |
| **Control Algorithm** | Move all sensors and computer on a cart | Verify proper output compensation depending on sensor inputs. |

**Table 5.2: Test plan at SFU**

The joysticks will be first used by the test engineers to verify throttle and angle control. A Panasonic Valve Regulated Lead-Acid 12V battery will be used on the mobile system suggested for mobile testing at SFU, which will be similar to the power supply on the test ship. The control system will use the ship's internal power supply. Once the initial sensors and motor unit have verified functionality, they will be installed on the test ship. Table 5.3 below shows the test plan for testing on the boat.

| **Component/sensor to be tested** | **Test Procedure** | **Results/Comments** |
|---|---|---|
| **Shutoff Command (switch)** | Pushing manually | Verify complete release of control to manual mode |

| | | |
|---|---|---|
| **Control Algorithm** | Remain idle and let boat move under water conditions | Verify proper output compensation depending on sensor inputs. |
| **Motor control** | Manually adjust destination coordinates | Ensure proper outputs are being communicated to and from the embedded computer |

**Table 5.3: Test Plan for boat**

## 6. Demonstration

The demonstration will include a video that will show the DPS operating on the test boat. It will show the user adjusting the desired position with the joystick, and the DPS response to correct the test boat's position.

## 7. Conclusion

Maintaining ship heading and position under manual control can be difficult and/or time consuming. A Dynamic Positioning System will perform these functions with reduced input from a human operator. Titanic Positioning, along with Think Sensors Research, will create a DPS-0 Control System. This system will be able to maintain position and heading using Manual Position Control and Automatic Heading Control. The operator will have fine tuning control of the GPS coordinates, and the DPS will adjust accordingly.

The DPS will use a GPS, a MRU, an anemometer, and a joystick as inputs to the control algorithm. The control algorithm will use PID feedback systems for optimal efficiency and stability. The controller algorithm will have: a wind feedforward, state estimators, wave filtering, and thruster allocation. Serial communication protocols will be used between all components to simplify design. The DPS will communicate with a motor controller to control the test boat's thrusters. The components of the DPS will be tested throughout the entire development phase.

# References

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[11] *NMEA 0183 Standard*. National Marine Electronics Association. November 2008.
Available: http://www.nmea.org/content/nmea_standards/nmea_0183_v_410.asp

## Appendix A: Cost Analysis

Table 1 below shows the financial breakdown of the project. Some of the components have been loaned from Think Sensor Research, and some of the costs, for example cables, connectors, and use of the boat are approximate. We expect that the total cost for the project will be within +- $500 of the projected costs.

| **Component** | **Cost ($)** | **Coments** |
|---|---|---|
| TSR-100 MRU | 8000 | Loaned from TSR for project |
| GPS | 500 | Loaned from TSR for project |
| USB to 4-Port Serial | 60 | |
| Embedded Marine Computer | 1500 | |
| Vaisala WMT52 Ultrasonic Wind Sensor | 1130 | |
| Cables, Connectors etc. | 500 | Approximate |
| Use of boat (Fuel and Captain's time) | 1000 | Approximate |
| Motor Controller for steering Hydraulic motor | 220 | |
| **Linear actuators to attach to throttles** | 2x130 = 260 | |

**Table 1: Financial breakdown of project**

Total cost for all the equipment as outlined in the table above: $3870
Total approximate cost of using boat: $1000
Total costs of project using $500 margin of uncertainty: $4370 - $5370

## Appendix B: Serial Communication and Data Parsing

### Serial Comunication

Our current computing device does not contain a UART port, hence an FTDI USB-Serial converter was used, which maps on USB port to 4 serial ports.
On our current development platform, I/O terminals are memory mapped and Linux operating system gains accesses to the port by opening file associated with the serial terminal. There, the port can be interpreted as a file, and reading/writing can be done by special kernel functions read() and write().

The flowchart in Figure x, describes the processes of configuring the serial port for sensing application. The chart applies to both MRU and GPS unless specified. Linux provides a library <termios.h>, in which the data structure for configuring port is defined.

The control options are set via logical AND/OR masking on a respective control flag with a predefined mask. It is best to configure the local flag to processes input canonically, which means that the read operation will block (wait) until an entire line is read into the buffer (specified by '\n' symbol). Software control must be turned on in order to control flow of data and process the handshaking. As character strings are read directly to buffer we must enable the terminal handler to discard the parity bit, so the character string can be read correctly.

In case of the MRU, output is set to directly transmit character from buffer (raw format) as no post processing is needed in our case.

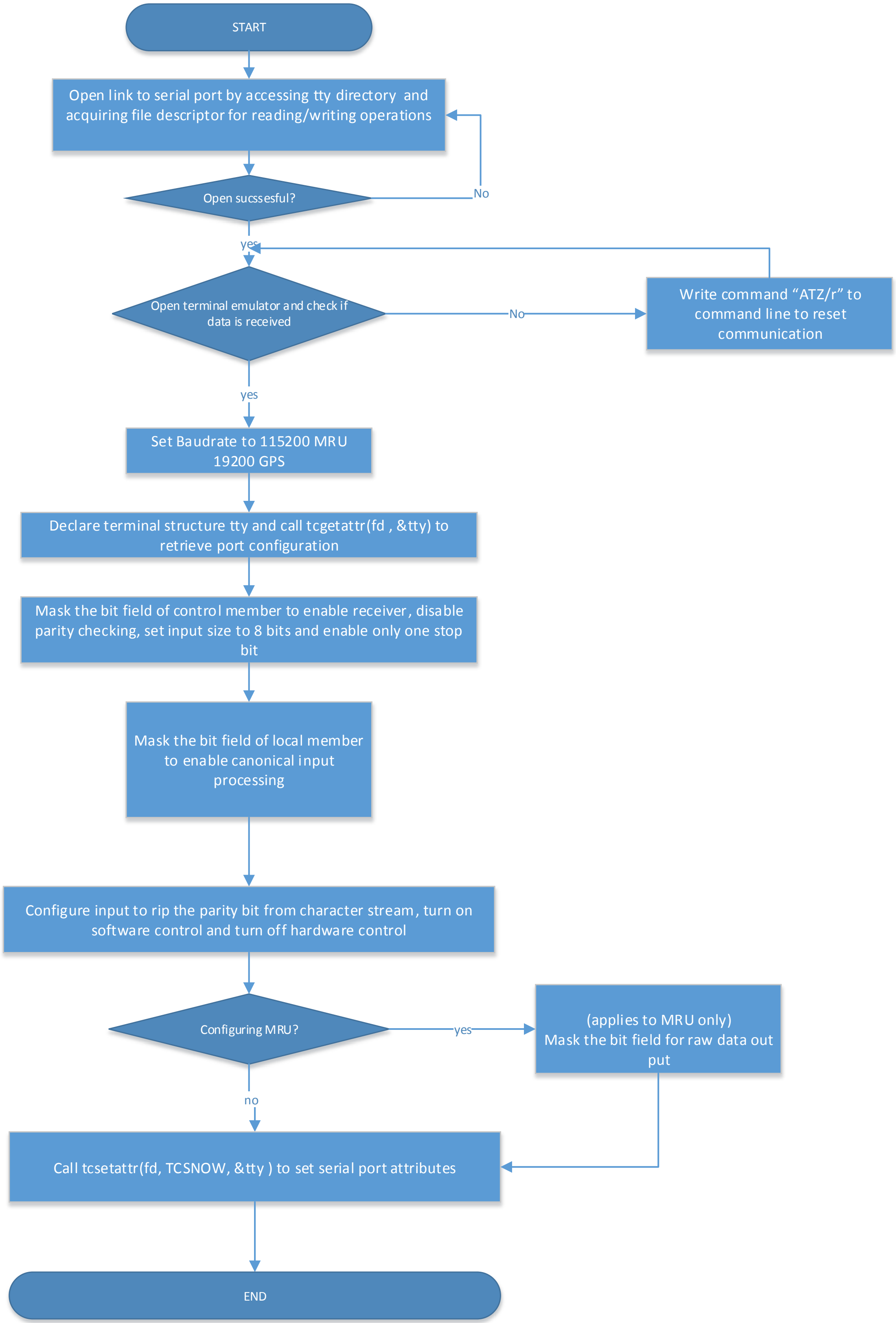

**Figure 1: Flowchart for serial communication**

## Parsing GPS and MRU Data

The Linux function read in canonical form will read entire line from serial port, which needs to be stored in a character buffer for parsing. In case of the MRU since only one string sentence type is acquired from the port, there is no need for header identification. This is not the case for GPS sentences as the antenna will receive sentences from various different satellites. The following chart specifies the steps of parsing NMEA string. MRU parsing can be done simply by calling sscanf(….) which is supported by C library.

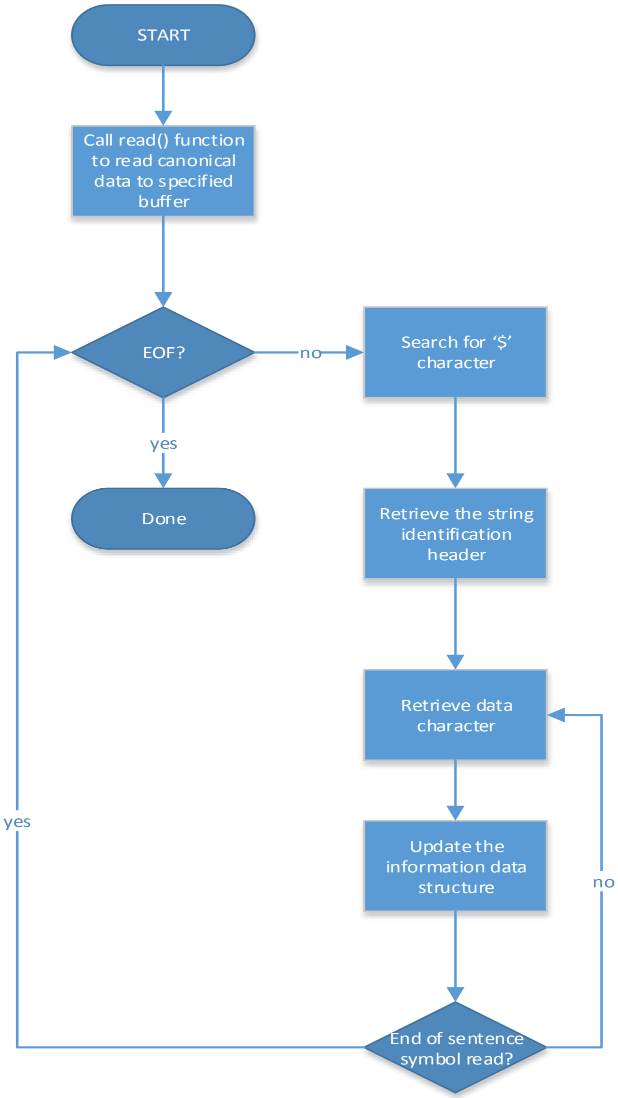

**Figure 2: Flowchart for parsing data**

## Appendix C: Mathematical Control Algorithms

In this section the mathematical concepts will be discussed for designing the PID controller. The green processing blocks in Figure zz will be discussed, and this section will show the mathematical models that will be implement in the controller. (Fossen)

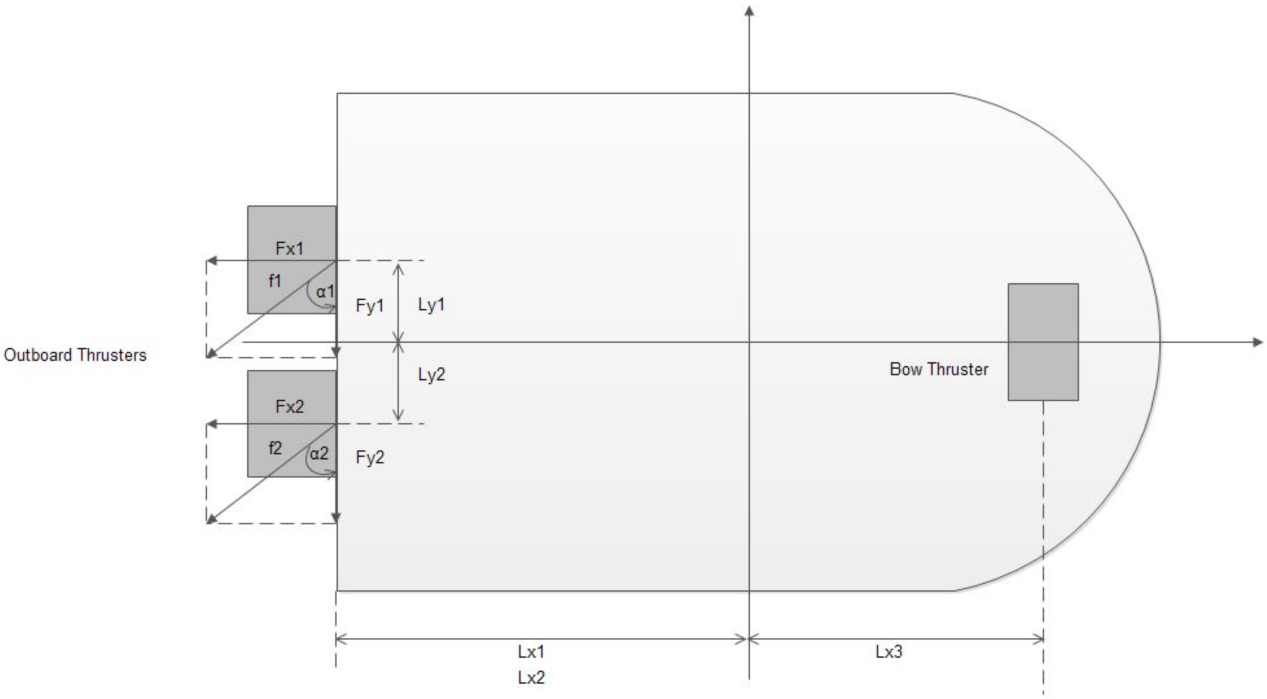

**Figure 3: Shows the variable used in equations**

### 1. PID

the PID controller has to include a proportional, differential, and integral component.

$$\tau_{PID} = -k_p n - k_d \frac{dn}{dt} - k_i \int_0^t n(\tau)d\tau = \; -R^T(n)k_p - R^T(n)k_d R(n)v - R^T(n)k_i \int_0^t n(\tau)d\tau$$

**Equation 1**

where n is the position vector, R is the rotation matrix, $k_p$, $k_d$, $k_i$ are gain constants, v is the velocity vector. Note $k_d$ should be chosen to be a diagonal matrix so that the rotation matrix doesn't effect the differential term. $_{PID}$ is the compensation force for the PID controller.

The GPS and MRU provide the data for the position vector and the rotation matrix. The gain constants need to be determined to best compensate for the rise time, steady state error, and overshoot.

## 2. Wind Feedforward

The wind feedforward system is used to compensate for the effects of wind on the position of the vessel. This section will describe the mathematical models that will be used to implement the wind feedforward system.

$$\tau_{wind} = \frac{1}{2}\rho_a V_{rw}^2 \begin{bmatrix} C_x(\gamma_{rw})A_{FW} \\ C_Y(\gamma_{rw})A_{LW} \\ C_N(\gamma_{rw})A_{LW}L \end{bmatrix}$$

**Equation 2**

where ${}_a$ is the density of air, $V_{rw}$ is relative wind speed, $C_X$, $C_y$, $C_N$ are wind coefficients in the surge, sway and yaw directions. $A_{FW}$ is the frontal projected area, $A_{LW}$ is the lateral projected area and L is the length of the boat. ${}_{rw}$ is the angle of attack. ${}^{\sim}{}_{wind}$ is the compensation force required to make up for the wind.

$$V_{rw}^2 = u_{rw}^2 + v_{rw}^2$$

**Equation 3**

$$\boldsymbol{\gamma_{rw} = atan2(v_{rw}, u_{rw})}$$

**Equation 4**

Where $u_{rw}$ is the velocity component in the surge direction and $v_{rw}$ is the velocity component in the sway direction.

$$u_{rw} = u - V_w \cos\,(B_w - \psi)$$

5.

**Equation 5**

$$v_{rw} = v - V_w \sin\,(B_w - \psi)$$

**Equation 6**

where $V_w$ is the wind speed from the anemometer, $B_w$ is the wind direction from the anemometer, and is the heading of the boat.

$$C_x = -c_x \cos\,(\gamma_{rw})$$

**Equation 7**

$$C_y = -c_y \sin\,(\gamma_{rw})$$

**Equation 8**

$$C_N = -c_y \sin\,(2\gamma_{rw})$$

**Equation 9**

Where $c_x$ is a constant [0.5, 0.9]. where $c_y$ is a constant [0.7, 0.95]. Where $c_N$ is a constant [0.05, 0.2].

Using the data from the anemometer the relative wind velocity in the surge and sway direction can be computed. Using the relative velocities, the relative wind speed and angle of attack can be calculated. Using the values and the constants ${}_a$ , $A_{FW}$, $A_{LW}$, $A_{FW}$, and L the compensation force ${}^{\sim}{}_{wind}$ can be computed.

## 3. Wave Filtering

Wave filtering can be done by cascading a low pass filter with a notch filter. The dominating wave frequency will be in the range of [0.05 Hz, 0.2 Hz]. In other words the waves within these frequencies produce large wave forces and need to be compensated for. In the case of smaller boats the bandwidth of the controller can be within the frequency range and can be compensated for with a cascaded filter design. The waves within this frequency range produce large oscillations over a mean wave force. The filtering should be done before the thruster controller so that the system doesn't try to compensate for the frequencies outside of the given range.

$$h_{lp}(s) = \frac{\omega_f^2}{(s^2 + 2C\omega_f s + \omega_f^2)} \frac{1}{(1 + \frac{s}{w_f})}$$

$\zeta = \sin(30)$, $\omega_f$ is the cutoff

**Equation 10**

$$h_n(s) = \frac{s^2 + 2\zeta\omega_n s + \omega_n^2}{(s + \omega_n)^2}$$

$\omega_n$ is chosen to be the peak frequency at zero speed

**Equation 11**

## 4. State Estimation

In industry it is common to use a linear Kalman filter after a non linear controller. A Kalman filter can estimate states from non linear DPS with a series of noisy measurements, and can remove white and coloured noise from the state estimate. The steady state solution to the Kalman filter is used for a linear filter.

$$\frac{dx}{dt} = Ax + Bu + Ew$$

**Equation 12**

$$y = Hx + v$$

**Equation 13**

w and v are zero mean gaussian white noise. Where A and H are state output matrices. y is the output and u is the input. E is the covariance and x is the state vector.

$$\frac{dx^{\wedge}}{dt} = Ax^{\wedge} + Bu + K_{\infty}(y - Hx^{\wedge})$$

**Equation 14**

$$K_{\infty} = P_{\infty}H^T R^{-1}$$

**Equation 15**

$$P_\infty = {P_\infty}^T > 0 \text{ is a solution to } AP_\infty + A^T + EQE^T + P_\infty H^T R^{-1} H P_\infty = 0$$

**Equation 16**

### 4.4.5 Thrusters Allocation

This section will discuss the mathematical model that will be used for the thrusters on the test boat and how to implement it so that the controller can adjust the position of the thrusters. The outboard thrusters are azimuth thruster and can rotate at an adjustable angle. The tunnel thruster at the bow can only move clockwise or counterclockwise.

$$F = ku$$

**Equation 17: F is force, k is coefficient of force, u is control input**

$$f^T = [Fcos(a), Fsin(a), 0]$$

**Equation 18: Where F is force and a is control angle**

$$\tau = \left[F_x, F_y, F_z l_y - F_y l_z,\ F_y l_x - F_x l_y\right]^T$$

**Equation 19: Where the $\tau$ is the force matrix, F is the forces in surge, sway, roll, and yaw directions. l is the moment arm.**

$$\boldsymbol{\tau = T(a)f = T(a)ku = \begin{bmatrix} X \\ Y \\ N \end{bmatrix}}$$

$$= \begin{bmatrix} \mathbf{cos}\,(\boldsymbol{a_1}) & \mathbf{cos}\,(\boldsymbol{a_2}) & \mathbf{0} \\ \mathbf{sin}\,(\boldsymbol{a_1}) & \mathbf{sin}\,(\boldsymbol{a_2}) & \mathbf{1} \\ \boldsymbol{l_{x1}}\mathbf{sin}(\boldsymbol{a_1}) - \boldsymbol{l_{y1}}\mathbf{cos}\,(\boldsymbol{a_1}) & \boldsymbol{l_{x2}}\mathbf{sin}(\boldsymbol{a_2}) - \boldsymbol{l_{y2}}\mathbf{cos}\,(\boldsymbol{a_2}) & \boldsymbol{l_{x3}} \end{bmatrix} \times \begin{bmatrix} \boldsymbol{k_1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{k_1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{k_1} \end{bmatrix} \times \begin{bmatrix} \boldsymbol{u_1} \\ \boldsymbol{u_2} \\ \boldsymbol{u_3} \end{bmatrix}$$

**Equation 20**

where X is sway, Y is surge, N is yaw. T is the thruster matrix where each column represents one thruster. the first 2 column are azimuth thrusters that can rotate along angle a with moment l. the 3rd column is a tunnel thruster. This matrix can be solved for the control input u, by linearizing the matrix and using a psuedo-inversion approach.

# Appendix D: ENSC 440 Functional Specification Dynamic Positioning Control System

## Table of Contents

# I. List of Figures

# II. List of Tables

# III. Glossary

**ABS** - American Bureau of Shipping

**ANSI -** American National Standards Institutes

**DPS** - Dynamic Positioning System

**DPS-0** - Is defined as a DPS that has a central manual position control and automatic heading control system.

**DPS-1** - Is defined as a DPS that has a central automatic and control and heading system. It also has a manual positioning control.

**GPS** - Global Positioning System

**HMI** - Human-Machine Interface

**MRU** - Motion Reference Unit

**NMEA** - National Marine Engineering Association

**OS** - Operating System

**SFU** - Simon Fraser University

# 1. Introduction

Marine vessels are sometimes required to maintain a heading or a position in situations where anchoring is difficult or impractical. An automated method of maintaining a heading or position is called dynamic positioning. Dynamic positioning is prevalent in the oil industry, where large transport ships dock at offshore oil platforms. The vessels are required to steadily maintain precise coordinates for hours while cargo is transferred. The position of the vessels must be held constant despite exterior forces such as wind, waves and tidal pull. This must be reliably done to ensure the safety of the workers on the rig and the ship, and that no product is spilled in the process.

A Dynamic Positioning System (DPS) is a control network that uses the ship's thrusters to adjust and maintain the ship's position according to feedback input from multiple sensors. The ship's location is adjusted and maintained by the DPS controller which makes a calculation based on the current location of the ship using a GPS, and sensor information gathered from wind and water current data.

The purpose of the project is to implement a DPS on a 10 meter long boat. The boat will maintain position and heading against external forces, such as the current in the Fraser River. The system will be expandable, and with the addition of further software, will be able to implement full dynamic positioning. The proposed requirements for the DPS are defined in this functional specification.

## 1.1 Scope

This document describes the functional requirements for a DPS, in compliance with the American Bureau of Shipping (ABS). Titanic Positioning is planning on controlling the thrusters of a ship to perform Dynamic Positioning. This will include Manual Position Control and Automatic Heading Control. This will be achieved by interfacing with a GPS, Motion Reference Unit (MRU), wind sensor, and a user interface.

## 1.2 Audience

This functional specification is written for the all members of Titanic Positioning and the members of Think Sensor Research that are involved in the project. The document shall be used as a reference for designing, testing, and project management. The functional specification outlines the requirements, test plan, safety and standards for the project. The document will be used to track progress and re-evaluate project goals.

# 2. Overal DPS Design

.

Table 1 below shows the different levels of automation that can be implemented on a marine vessel.

| | |
|---|---|
| Manual Control | Human operator controls ship without DPS. |
| Manual Position Control | Human operator uses joystick to manually set coordinate destination for DPS. |
| Automatic Position Control | GPS coordinates are set with keyboard from a distance and have automatic fine tune control. |
| Automatic Heading Control | DPS maintains the direction automatically based on data from the MRU. |

Table 1: Definitions of important terminology

2.1 Background (not sure if background fits here though)

Dynamic positioning systems are used on ships for heading control and station keeping. Dynamic positioning is used when it is impractical or impossible to anchor the ship. When large ships approach delicate ocean structures (eg, offshore oil platforms), extreme care has to be taken to avoid dangerous situations. Previously, ship captains had to carefully maneuver their ships manually. Station keeping was performed manually, which could be stressful and conducive to error during cargo transfer operations that can last several hours. Alternatively, anchor nets and anchors could be used to prevent the ship from moving or turning, however nets are difficult and time consuming to set up correctly, especially around fixed structures due to entangled lines. If it is possible to use anchors, multiple anchors would be needed to ensure that the ship does not turn. The DPS would be able to solve these problems by performing station keeping automatically by correcting for environmental forces without using anchors or constant manual input from an operator

## 2.2 Design Approach

Titanic Positioning will be constructing a DPS-0 system with the ability to upgrade to DPS-1 at a later date. DPS-0 is a basic dynamic positioning system that offers manual position control, and will maintain the position and heading of a ship. To do this, the DPS control system will need the current data for the position and heading of the ship, and the ability to control the ship's motors and thrusters to automatically reposition it. For added control, a wind sensor will also be used, with expansion opportunities for a water current sensor which is required for DPS-1. Table 2 below defines the DPS-0 and DPS-1 requirements according to the American Bureau of Shipping.

| | |
|---|---|
| DPS-0 | a DPS that has a central manual position control and automatic heading control system. |
| DPS-1 | Is defined as a DPS that has a central automatic and control and heading system. It also has a manual positioning control. |

Table 2: defines different class of Dynamic Positioning

### 2.3.1 Sensors and Inputs

To properly maneuver a ship, the DPS control system needs to detect the location (coordinates), orientation and heading of the ship. The location coordinates of the ship will be acquired from the GPS. The heading of the ship will be acquired from the Motion Reference Unit (MRU). The MRU also relays data when the ship pitches and/or rolls. Since the GPS will be at the highest point of the ship, when the ship pitches or rolls the GPS will swing and the coordinate reading will not always be taken from the center of the ship. The MRU will be used to correct for the error in the positioning data caused by the swing of the GPS.

The DPS control system will have a wind sensor and a water current sensor. Wind and water forces must be compensated for during maneuvers or station holding. For a DPS-0 the water current sensor is not required, but it is something that is needed once the project is expanded.

The SFU Test Ship uses two outboard motors that can be turned for steering. An angle sensor will be used on the motors so the control system will know which direction the motors are pointing. This will create feedback, which will be safer when maneuvering the ship.

### 2.3.2 Serial communication

The control system will use serial connectors for all input and output signals to retain wiring simplicity and modifiability. The communication lines between the sensors and an embedded computer will use standard marine insulated wiring.

### 2.3.3 Embedded Computer

A ship using the Dynamic Positioning System (DPS) is run by the control system on an onboard embedded computer. The embedded computer will be housed in a water-tight environment to avoid electrical and fire hazards, and to preserve the integrity of the control system. The embedded computer will have no moving parts, making it more resistant to the shocks and vibrations that are common on ships.

The embedded computer will use a Linux operating system (OS) which will facilitate the expansion of the control system to a higher level DPS at a later date. An OS also makes communicating with the display computer simpler, since the display will require stack communication and an OS has built in function for stack communication. Several of the drivers for the sensors are built in to the OS. The OS provides preconstructed matrix math libraries that will be necessary for the DPS control system. The embedded computer will run Linux because it is well suited for real-time performance and software stability. Using an OS will better enable a large group to work on the project simultaneously.

The DPS will require a human-machine interface (HMI) for operators. The HMI will let operators set coordinates, fine-tune positioning adjustments, and provide visual feedback. The DPS control system will have one station with a display screen, a keyboard for Automatic Position Control, and a joystick for Manual Position Control. In the proof-of-concept system, the input and display will be handled by the embedded computer. In the production DPS control system, the interface will have a dedicated computer to minimize time delays, and will have two stations.

### 2.3 .5 Thrusters

Figure 1 below shows the SFU test ship and projected target ship with the motor and thruster layout. The SFU Test Ship is shown with two outboard motors and one bow thruster. The SFU Test Ship uses two 250 HP outboard motors with a limited range of motion. The test ship bow thruster can be run in either clockwise or counter clockwise direction to assist in maneuvering.

The Projected Target Ship has two fixed diesel motors with variable tilt props for propulsion, and four diesel-electric maneuvering thrusters for steering and lateral movements. Figure 1 below shows the motor (black) and thruster (gray) placement on the two ships. Figure 2 shows the proof of concept ship on which the prototype system will be implemented.

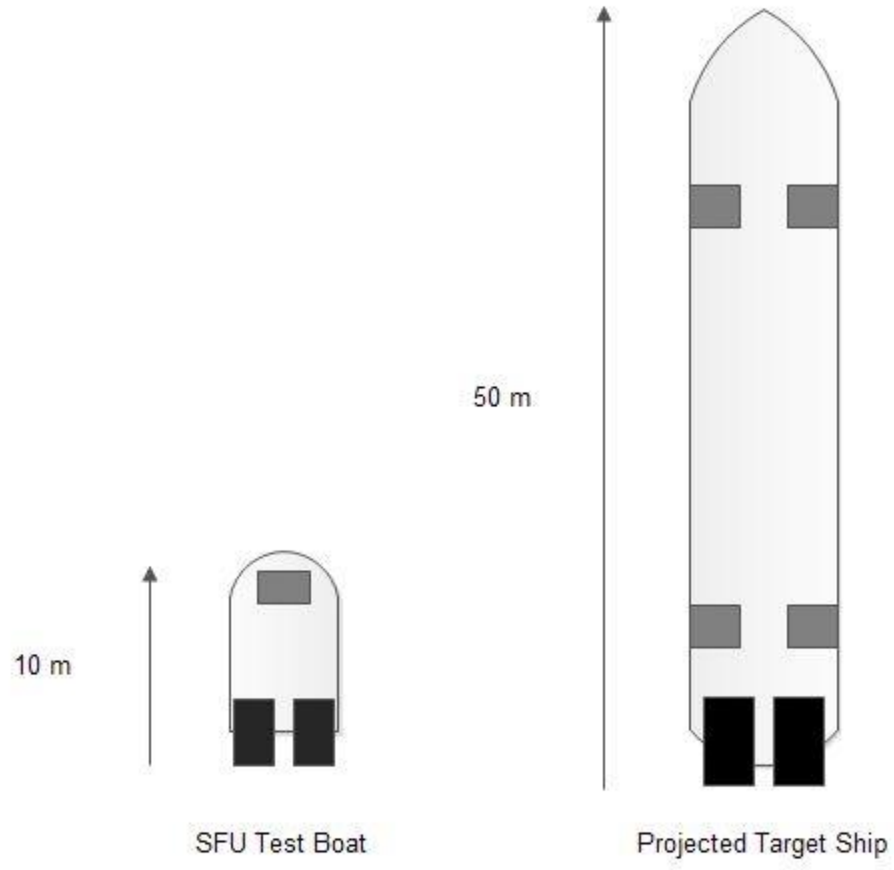

Figure 1: The SFU Test Ship and the Projected Target Ship comparison (not to scale).

Figure 2: The SFU Test Ship

Figure 3 below shows an overview of the system inputs, outputs and controls.

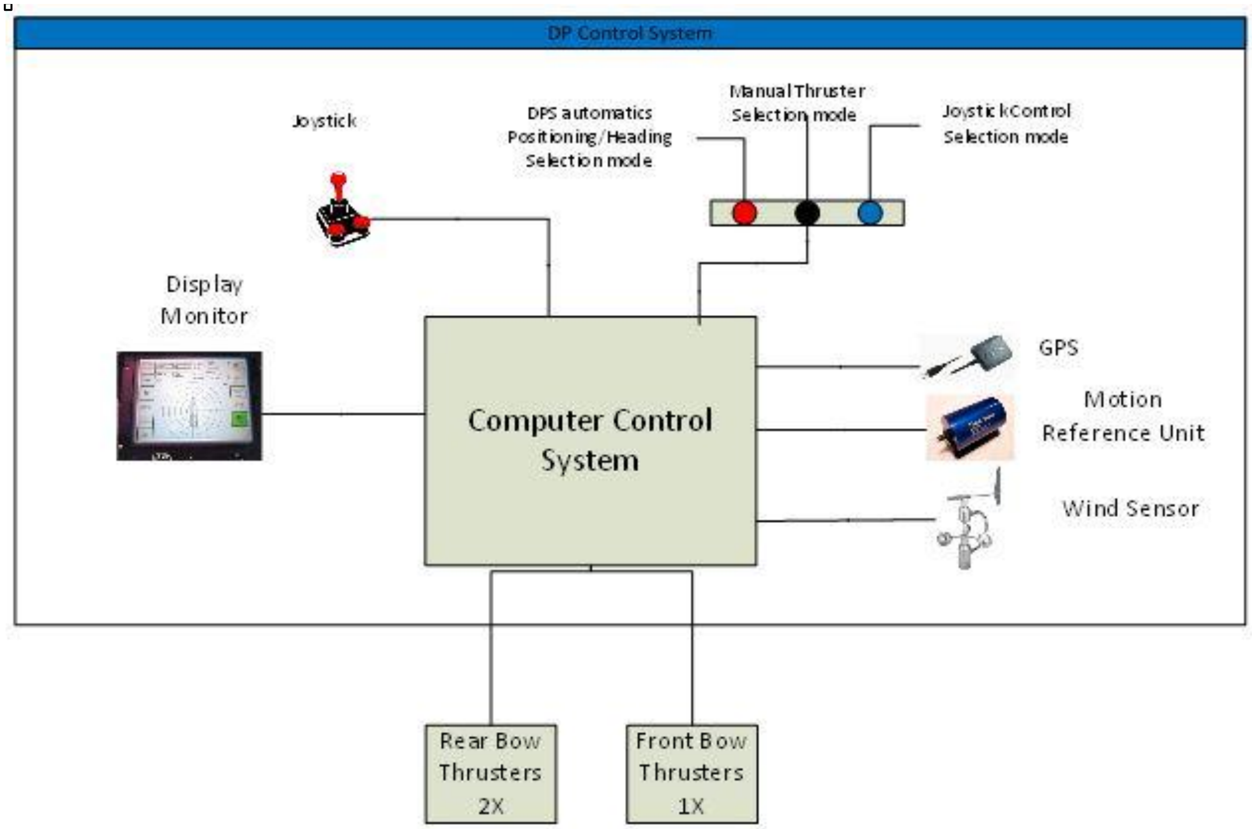

Figure 3: DPS overview

## 3. Project State

During the course of the term, Titanic Positioning will complete a DPS-0 proof-of-concept design. The project will be expandable for prototype and production purposes. The design will also be expandable for higher classes of Dynamic Positioning, such as DPS-1. The project will be continued after the term by a joint effort from some members of Titanic Positioning and Think Sensor Research. Table 3 shows the differences between the different stages of design.

The proof-of-concept design will use a development board with a separate USB to serial adapter. The USB to serial adapter will be enclosed in a rigid container, with the wires temporarily secured. In the production case, the display computer will incorporate a trackball and keyboard into one module instead of separate components. The projected target ship will also utilize fanning lasers that will be set up on the oil rigs as an additional method of measuring that the ship is in place. In the production version a North-seeking gyroscope compass will be used. The North-seeking gyroscope is needed because the magnetic sensor in the MRU is susceptible to interference from the metal structure of the ship.

| | **Proof-of-Concept** | **Prototype** | **Production** |
|---|---|---|---|
| **DPS-0** | Off-the-shelf components | Off-the-shelf components | Off-the-shelf components |
| **DPS-0** | Development board with external additional serial ports as the control computer | Embedded computer with enclosed serial ports as the control computer | Embedded computer with enclosed serial ports as the control computer |
| **DPS-0** | Temporary secured wires | Permanently secured wires | Permanently secured wires |
| **DPS-0** | Reused marine GPS | New robust marine GPS | New robust marine GPS |
| **DPS-0** | Display, keyboard, and joystick controlled by development board. | Display, keyboard, and joystick controlled by dedicated computer. | Display computer will have a built in trackball and keyboard. |
| **DPS-1** | | Addition software for Automatic Position Control (DPS-1) | Addition software for Automatic Position Control |
| **DPS-1** | | Water current sensor (DPS-1) | Water current sensor |
| **DPS-1** | | | Fanning lasers on dock |
| **DPS-1** | | | North Seeking Gyroscope |

Table 3: Comparison of proof of concept, prototype and production

## 4. Constraints

The project will be limited by  financial and time constraints. The SFU Test Ship also has scheduling constraints. The ship is difficult to access as it requires the coordination of multiple parties. Operating the SFU Test Ship will have both costs for fuel and for the time of the captain. Titanic Positioning will create efficient testing plans when using the SFU test ship, to minimize costs. A design constraint includes the size of the ship and the motor arrangement. Since the ship in use has fewer motors and is smaller than a typical vessel, the controls will be limited and the steering controls will be different. The direction of the ship will first be set using the bow thruster, and then the outboard motors will power the ship in that direction, whereas the target ship has four side thrusters which will allow for lateral movement of the ship. The heavier target ship will also have more inertia, which will change the amount of time and power required from the thrusters.

The time requirements can be an issue since there are only four months to put together a proof-of-concept. As a result, instead of attempting to do full dynamic positioning, we will implement a DPS-0 system which with further addition of software will be able to do full dynamic positioning protocol and time, and specific sentence formats for a 4800-baud serial data bus”(2). This standard supports serial communications in a marine environment.

## 5.Testing Plan

Titanic Positioning will test the system throughout the entire development phase. The sensors will first be tested individually, and then together on our development system. Table 4 outlines the required testing that will be done at SFU in the lab:

| **Component/sensor to be tested** | **Test Procedure** | **Results/Comments** |
|---|---|---|
| **MRU** | Tilting and measuring output signal | Ensure the MRU communicates with the embedded computer and that the reading is accurate |

| | | |
|---|---|---|
| **GPS** | Develop a mobile system and move around campus | Ensure location accuracy and communicates with embedded computer |
| **Wind sensor** | Simulating wind using a fan | Ensure the accuracy of wind direction and communicates with embedded computer |
| **Motor Control** | Simulating maneuvers | Ensure proper outputs are being communicated to and from the embedded computer |
| **Shutoff Command (switch)** | Pushing manually | Verify complete release of control to manual mode |
| **Control Algorithm** | Move all sensors and computer on a cart | Verify proper output compensation depending on sensor inputs. |

Table 4: Test plan at SFU

The joysticks will be first used by the test engineers to verify throttle and angle control. A Marine Deep Cycle 12V battery will be used on the mobile system suggested for mobile testing at SFU, that will be similar to the power supply on the test ship. The control system will use the ship's internal power supply. Once the initial sensors and motor unit have verified functionality, they will be installed on the test ship. Table 5 shows the test plan for testing on the boat.

| **Component/sensor to be tested** | **Test Procedure** | **Results/Comments** |
|---|---|---|
| **Shutoff Command (switch)** | Pushing manually | Verify complete release of control to manual mode |
| **Control Algorithm** | Remain idle and let boat move under water conditions | Verify proper output compensation depending on sensor inputs. |

|  |  |  |
|---|---|---|
| **Motor control** | Manually adjust destination coordinates | Ensure proper outputs are being communicated to and from the embedded computer |

Table 5: Test plan for boat

## 6.Engineering Standards

**ABS standards (DPS-0 and DPS-1)**

ABS defines the standards for the classification of the level of DPS. The ABS defines the necessary requirements that must be met before a DPS can be commissioned. (1)

**American National Standards Institute (ANSI)**

The DPS shall comply with the ANSI standards. (3)

**Federal Communications Commission (FCC)**

Communications protocols shall be in compliance with the FCC. (4)

**National Marine Electronics Association (NMEA) - 0183 Standard**

“The NMEA 0183 Interface Standard defines electrical signal requirements, data transmission

## 7. Sustainability and Safety

### 7.1Safety

**Electrical and Fire:** On the vessel there are several electrical and fire safety issues that need to be considered. Even though we plan to use as few loose wires as possible, it is important to ensure all wires are properly secured and insulated. Properly secured and insulated wires will avoid wire damage and prevent overheating. On the boat there is some high power equipment, such as the thrusters. When working with these thrusters, extra precaution will be taken. For example, fuses and breakers should be used to prevent overheating.

Another very important safety precaution is the functionality of the emergency stop for the DPS. The emergency stop should be the first thing to be tested since if there are problems with the DPS during testing, it should be able to quickly turn of the DPS system and return to manual drive.

**Mechanical:** It is important to stay clear of all moving parts, such as the propellers of the thrusters when the system is running, even when the props are not spinning. It is also important to avoid the moving parts even when they are currently off because someone may not realize and turn on the motors.

Since the motor control is hydraulic and needs an electrical autopilot interface, it is important to install it correctly to avoid spilling hydraulic fluid. It is also possible to get bubbles in the hydraulic fluid, which can cause problems with the functionality of the motor.

**Software:** The DPS software should have built in safety limits for motor speed and environmental conditions. For example the DPS should not turn the motors on to full power to maintain position and the software should have a limit so the motors do not exceed a specified threshold. The DPS software will warn the user if the weather conditions are not safe enough to run the DPS. For example, if the boat is stuck in a major storm, then it would not be safe to try to maintain position with any accuracy, and it would not be safe to load cargo from a barge.

There is also a need for fault detection software. For example, if the hydraulic motor line or the throttle cable were to malfunction, then a fault should be detected. The user will be informed by the software if any of the sensors send faulty and unreliable data.

**Water:** Life jackets should be worn when on deck of the ship. The DPS should not be tested while other ships are in the area, or people are in the water.

**Environmental:** During the project we will be using deep cycle marine batteries, which can be an environmental problem if not recycled properly.

## 7.2 Reliability

The design will  be reliable and consider all points of possible failure. There may be problems caused by the environment that the system will be placed into, hence the design should take those into consideration. Grounding problems could be an issue since some device may not have the grounds tied together. This problem could be fixed by connecting all the grounds to a single node. An example of possible failure is if wiring connectors get moisturized, in order to prevent this hazard, marine graded wires and connectors must be secured in a safe location

All components would be insulated from extreme temperatures to ensure reliable functionality. Several components will be inside an electrical room on a ship, and therefore would be sheltered from the outside environment. Other components will be chosen to have a wider operational temperature range, like the wind sensor.

For the proof of concept redundancy will not be considered, however once the design is expanded to a prototype or higher class of DPS redundancy will be incorporated.

## 7.3Environmental Impact

The design shall consider the project lifetime of the components to minimize electronic waste and maximize industrial performance.

Table 6 lists the expected lifetime of the components that will be used in this project:

| Component/sensor name | Approximate Lifetime ( years) |
|---|---|
| MRU | 10 |
| GPS | 5-10 |
| Embedded computer | 7 |
| Wind Sensor | 2-5 |

Table 6: Expected lifespan of the components/sensors

The embedded computer can have a lifetime of over 7 years, which would be advantageous because controller will not need to be replaced on a regular basis and it will also minimize the need for maintenance.

The deep cycle marine battery used for testing components in the lab will be a recycled battery that was used on a previous project. Once testing is done with the battery, it will be stored for future project testing purposes

# 8.Conclusion

Maintaining ship heading and position under manual control can be difficult and/or time consuming. A Dynamic Positioning System will perform these functions with reduced input from a human operator. Titanic Positioning, along with Think Sensors Research, will create a DPS Control System, starting with a DPS-0 system on a test ship as a proof of concept, and expanding it to DPS-1 at a later date. This system will be able to maintain position and heading using Manual Position Control and Automatic Heading Control. The operator will have fine tuning control of the GPS coordinates, and the DPS will adjust accordingly.

The DPS Control System will be on an onboard embedded computer, running a Linux OS. Linux was chosen to simplify cooperative coding, for its software stability, and future expandability of the DPS Control System. Using OS will make the communication with the display station simpler. The sensors that the proof of concept system will use are a GPS, a MRU, and a wind sensor. The MRU is used for compensating for ship pitch and roll, and provides heading information. The sensors and communication with the embedded computer will be tested at SFU. The Control System will have emergency warnings and shutoffs, which will also be tested both at SFU and on the test ship. Later systems will include a water sensor, Automatic Position Control, and greater redundancy and backups for improved reliability.

Titanic Positioning will ensure that the system will be long lasting and reliable. Measures will be taken to address electrical and moisture concerns on the ship to ensure system integrity. Precautions against fire, electrical, and mechanical hazards will be taken when installing and operating the Control System. The proof of concept system and future systems will comply with standards set by ABS, ANSI, FCC, and NMEA.

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