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Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions

Part 1: Sensor and control system modelling
Part 2: Modelling the vehicles and the dock
Part 3: Software Manual

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Abstract

Docking an unmanned underwater vehicle (UUV) with a submerged submarine in littoral waters in high sea states requires more dexterity than either the submarine or streamlined UUV possess. The proposed solution uses an automated active dock to correct for transverse relative motion between the vehicles. Acoustic, electromagnetic, and optical sensors provide position sensing redundancy in unpredictable conditions. The concept is being evaluated by building and testing individual components to characterize their performance, errors, and limitations, and then simulating the system to establish its viability at low cost.

This report is one of three documenting the simulation. Part 1 discusses how system sensors and controls are modelled, Part 2 discusses vehicle and dock dynamics modelling, and Part 3 is a user manual.

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Nomenclature

General

Symbol	Units	Description
m	n/a	Number of workspace degrees of freedom
n	n/a	Number of configuration space degrees of freedom
r	n/a	Number of independently controlled actuators
t	s	Time
t_0	s	Initial time

Environment

Symbol	Units	Description
D	m	Water depth
H	m	Wave height
H_s	m	Significant wave height of an irregular sea state.
Q	%	Water turbidity for optical sensor
V_s	m/s	Speed of sound in water

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Vehicle geometry

Symbol	Units	Description
$\mathbf{CG}_i$	m,degree	Link i's rigid body reference frame
$\mathbf{J}_i$	m,degree	Joint i's reference frame description
$\mathbf{L}$	m	Position vector where the UUV is expected to enter the docking envelope
d_2	m	Prismatic joint displacement of $\mathbf{J_2}$
d_2^*	m	Desired prismatic joint displacement of $\mathbf{J_2}$
$\mathbf{s}$	m	Position vector of the sensor relative to the docking mechanism base frame
$\mathbf{p}$	m	The relative position vector as perceived by the stage 2 PSSs
$\mathbf{v}_{sub}$	m/s	Velocity vector of the submarine
$\mathbf{v}_{UUV}$	m/s	Velocity vector of the UUV
x_p	m	The x component of $\mathbf{p}$, the relative position vector as perceived by the Stage 2 PSSs
y_p	m	The y component of $\mathbf{p}$, the relative position vector as perceived by the Stage 2 PSSs
z_p	m	The z component of $\mathbf{p}$, the relative position vector as perceived by the Stage 2 PSSs
y	m	Offset distance between the UUV's parallel path to the submarine's
y_{LL}	m	Lateral distance limit when the β has attenuated to zero.
y_{UL}	m	Lateral distance limit when the UUV begins attenuating β.
$y_d(t)$	*	Desired vehicle trajectory as a function of time
α	degree	Bearing of submarine from UUV relative to docking procedure heading
α_i	degree	Bearing of submarine from UUV relative to docking procedure heading that triggers UUV to begin maintaining a constant bearing γ
β	degree	The relative heading between the UUV's heading and the docking procedure's heading.
γ	degree	Bearing angle of sub relative to UUV's heading
$\delta\theta_1$	degree	The angle of $\mathbf{p}$ relative to the sensor frame
θ_1	degree	Revolute joint displacement of $\mathbf{J_1}$
θ_1^*	degree	Desired joint displacement of $\mathbf{J_1}$
ϕ_1	degree	Pitch angle of wing fairing on the docking system

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Sensors

Symbol	Units	Description
E	*	Noise error standard deviation for a sensor
$E_{R_{max}}$	m	Error standard deviation as percentage of range at $R_{max|reduced}$.
I	W/m^2	Intensity, the average amount of sonic energy transmitted per unit time per unit of area
I_s	W/m^2	Intensity at some distance r_s assuming spherical spreading
I_o	W/m^2	Intensity at a unit distance of 1m assuming spherical spreading
P	W	Power of an acoustic signal; energy emitted per unit time
S	m,degree	Sensor reference frame
SNR	dimensionless	Signal to noise ratio (non-logarithmic)
$SNR(dB)$	dB	Signal to noise ratio (in Decibels)
RL	dB	Acoustic signal level at receiver
SL	dB	Acoustic signal level at transmitter
TL	dB	Acoustic signal transmission losses
R	m	The range or distance between the UUV and the Sensors
R_{min}	m	A sensor's minimum distance for detecting the position of the source
R_{max}	m	A sensor's maximum distance for detecting the position of the source
$R_{max|reduced}$	m	A sensor's reduced maximum distance due to unfavorable environmental conditions
V_v	m/s	Component of acoustic signal velocity that is parallel with vector sensor array
d	m	Distance between acoustic vector PSS' sensors
f	Hz	Frequency of oscillation in Hz
k_r	dimensionless	PSS error sensitivity factor to range
k_b	dimensionless	PSS error sensitivity factor to relative bearing angle
r_s	m	Distance from sonic source (spherical spreading)
r_o	m	Unit distance (1m) from sonic source
K_β	degree	Camera horizontal field of view angle
K_α	degree	Camera vertical field of view angle
Ψ_β	degree	Light source horizontal field of illumination angle
Ψ_α	degree	Light source vertical field of illumination angle
δt	*	The differential arrival time of sinusoidal signal peaks for vector PSS
κ_β	degree	Relative bearing vision of the camera
κ_α	degree	Relative azimuth vision of the camera
ϕ_d	degree	Instantaneous phase difference of acoustic signal between acoustic vector PSS' sensors
ψ_β	degree	Relative bearing illumination of the light
ψ_α	degree	Relative azimuth illumination of the light
ω	rad/s	Frequency of oscillation in rad/s

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Signal modifiers

Symbol	Units	Description
N	n/a	Number of input signals for sensor fusion block
RC	s	Low pass filter time constant
c_j	*	Confidence factor of input signal j, for weighing signal importance for sensor fusion block
f_c	Hz	Low pass filter cut off frequency
s_{avg}	*	The weighted average of the input signals for sensor fusion block
s_{min}	*	Signal limiter minimum limit
s_{max}	*	Signal limiter maximum limit
ϵ	dimensionless	Low pass filter smoothing factor
σ_j	*	Signal j's standard deviation
τ_s	s	The low pass filter's sampling period.

Controllers

Symbol	Units	Description
$\mathbf{G}_P$	*	MIMO Proportional gain matrix
$\mathbf{G}_I$	*	MIMO Integral gain matrix
$\mathbf{G}_D$	*	MIMO Derivative gain matrix
G_P	*	Single-input/single-output (SISO) Proportional gain
G_I	*	SISO Integral gain
G_D	*	SISO Derivative gain
N_i	n/a	Number of input signals
N_o	n/a	Number of output signals
e	*	SISO Error in the input signal
$\mathbf{e}$	*	MIMO error in input signal vector
$\mathbf{s}_i$	*	MIMO input signal vector
$\mathbf{s}_t$	*	MIMO setpoint signal vector
$\mathbf{s}_o$	*	MIMO output signal
s_i	*	SISO input signal
s_t	*	SISO setpoint signal
s_o	*	SISO output signal

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1 Introduction

1.1 Overview

Dynamic Systems Analysis Ltd. (DSA) is developing, for DRDC Atlantic, an underwater multi-vehicle simulation of an Unmanned Underwater Vehicle (UUV) docking with a submerged slowly moving submarine. The purpose of this development is to provide an ability to evaluate UUV docking strategies through the use of virtual prototypes. This will allow for rapid iterative improvements to the system's preliminary design without the need for expensive sea trials. The following document is part 1 of a 3 part report. It describes work completed between September 1, 2011 and March 31, 2014 by DSA towards the development of a control system code infrastructure along with various control system component models. Part 2 of the report documents the development of the dynamics and hydrodynamics models while part 3 consists of a software manual.

This dynamic simulation software is being developed using DRDC's Ship Mechanical System Application Programming Interface (SMS API). The SMS API is a simulation library that provides high fidelity multi-body simulation capabilities suitable for engineering analysis. The SMS API has been used in the past to simulate the launch and recovery of a small surface based rescue vessel from a naval frigate using a boomcrane, cables, and a winch. Here, the SMS API's capabilities are being extended to provide high fidelity simulations of various scenarios of a UUV docking to a slowly moving submarine.

Docking a UUV to a submerged submarine is not a trivial task. Both the submarine and UUV are free to move independently in all 6 degrees of freedom. In addition, to manoeuver and remain controllable, the submarine and UUV must maintain enough forward velocity relative to the fluid so their control surfaces can maintain control authority. Both the submarine and UUV are also subject to environmental disturbances such as from wave forcing which can oscillate them in any of their 6 degrees of freedom. To automatically dock the UUV to the submarine under such environmental loading multiple control systems are required to work in unison (*i.e.,* the submarine autopilot, UUV autopilot and the docking system controllers).

The chosen strategy for quickly and reliably recovering a UUV from a slowly moving submarine is to use an active docking arm mechanism (manipulator) mounted to the submarine. This approach was chosen over passive docking mechanisms because of the limited lateral maneuverability of the UUV [1]. The UUV will focus on closing in on the dock longitudinally, a degree of freedom streamlined vehicles tend to have more control over [1]. At the same time, the docking arm mechanism keeps its end effector (the capture mechanism) aligned with the UUV laterally, following the UUV's motion in a plane transverse to the submarine's centerline.

This document is broken up into five sections. Section 2 provides a brief overview of the simulation scenario and its components. Section 3 discusses the implementation and design of control systems and navigational routines. Section 4 presents verification tests and simulation results to demonstrate the proper functionality of various simulation components. A preliminary analysis demonstrating the docking mechanism's ability to control the location of its end effector in various sea states is provided in Section 4.10. Finally some conclusions and a list of recommended future work can be found in Sections 5 and 6 respectively.

1.2 Completed tasks

The software is currently able to complete both stage 1 and stage 2 of the UUV recovery simulation. Both vehicles are modelled using 6 DOF rigid body models. The docking mechanism is modelled using the articulated body algorithm (ABA) where each link is a 6 DOF rigid body that is restricted to motion about a single degree of freedom joint when attached to

another upstream RigidBody.

Both vehicles have coefficient based maneuvering hydrodynamics models. The coefficients will be provided by DRDC software titled DRDC Submarine Simulation Program 5.0 (DSSP50). However, to date, simplified coefficient manoeuvring models based on estimated coefficients is used for this stage of development.

Free surface effects, or wave loading, for the submarine are accounted for using a seakeeping model provided by another DRDC software titled ShipMo3D. For the UUV and docking mechanism, the small body approximation is made and a Morison based modelling approach is employed for handling wave loading.

Hydrodynamic interactions between the vehicles (eg, the hydrodynamic effects for the submarine on the dock and UUV) are a low DRDC priority at this early stage of development. These effects are not currently modelled but are likely to be incorporated at a future date.

A software infrastructure and high level user interface for building vehicle autopilots and connecting sensors and appendages has been created. Access to all controller component model parameters is available via the component initialization files. Simulations have been conducted demonstrating two autopilot modes of operation: steady flight mode and homing mode.

Four positioning sensor systems (PSS) have been implemented. These include an optical PSS, two electro-magnetic (EM) PSS, and an acoustic PSS. Simplified place holder sensor models were developed until high-fidelity sensor models are developed and implemented.

Multiple UUV homing strategies were developed and tested in the simulation software in collaboration with DRDC. A constant bearing homing strategy was settled on since it allowed the UUV to travel at reduced velocities, preserving it's limited energy reserves, while the submarine could rely on its much larger energy reserves and higher speeds to close the distance between the two. The strategy is discussed in detail in Section 3.3.3.

Two active dock mechanism models were considered, one with mechanical actuation and one with hydrodynamic actuation. Both were implemented and tested in simulation however a decision was made by DRDC to focus development efforts on the hydrodynamically actuated mechanism. Thus only the hydrodynamically actuated docking mechanism is discussed in this report.

A model predictive controller (MPC) for controlling the docking mechanism was implemented in the software. However, the implemented controller did not meet performance expectations and a PID controller was used in its place. A more advanced controller will likely replace the PID based controller.

This report is broken up into 3 parts and has been provided to DRDC along with the software source code and all simulation initialisation files in accordance with the requirements of this project.

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2 Simulation scenario overview

2.1 Environment

The simulations will be conducted near the ocean surface, in littoral waters, where oscillatory wave forces may have a significant effect on the motions of the submarine, the UUV, and the docking mechanism. The simulation has the submarine maintaining a depth of $D = 15$ m while travelling through waves with a significant wave height as high as $H_s = 5$ m corresponding to sea state 6 on the World Meteorological Organization sea state code. This scenario is illustrated in Figure 1.
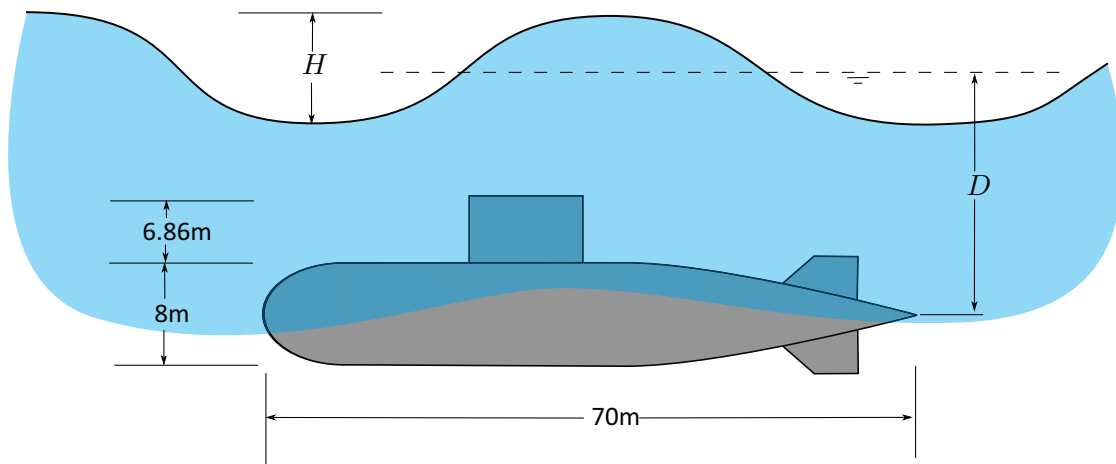
Figure 1: The dimensions of the submarine, showing it in waves where H is the wave height and D is the depth of the submarine from the calm water line.

2.2 Vehicle geometry

The geometry of the submarine being modelled is the DREA standard submarine model [2]. As shown in Figure 1, it has a length of 70 m, and a hull diameter of 8m. The sail is an extra 6.86 m height above the top of the hull. The submarine has a thruster for speed control, rudder planes for heading control, and stern and bow planes for pitch and depth control.

The UUV is a 2 m long generic, cylindrical, streamlined vehicle with a 0.2m diameter hull as shown in Figure 2. It has a thruster for speed control and stern/rudder planes for pitch and heading control.

Figure 2: The dimensions of the UUV.

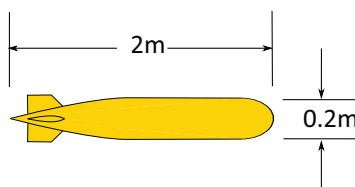| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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2.3 Docking mechanism

The docking mechanism is a 2 DOF planar serial manipulator as shown in Figure 3. It is mounted to the hull of the submarine (for this work, to the starboard side) as shown in Figure 4. It consists of a revolute joint followed by a prismatic joint, which creates a planar mechanism. The end effector is able to move to any location in a plane transverse to the submarine's longitudinal axis within the limits of the joints. There is the possibility for a 3rd joint to allow the mechanism to yaw. However, this is currently being ignored. Similarly, the capture mechanism (the end effector), is also ignored.
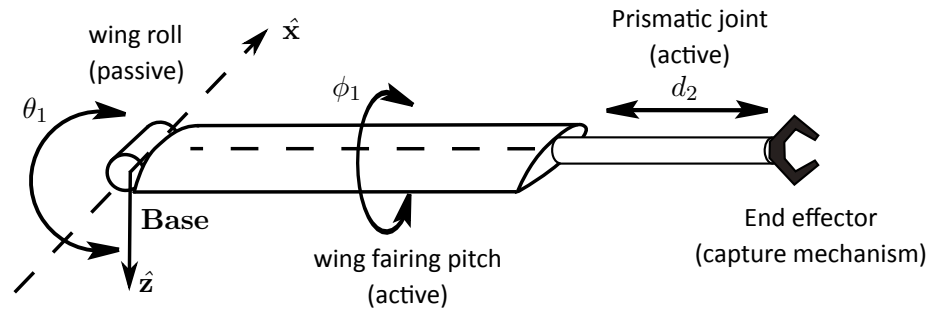

Figure 3: A diagram showing the docking mechanism's degrees of freedom, actuated fairing and the end effector (capture mechanism).
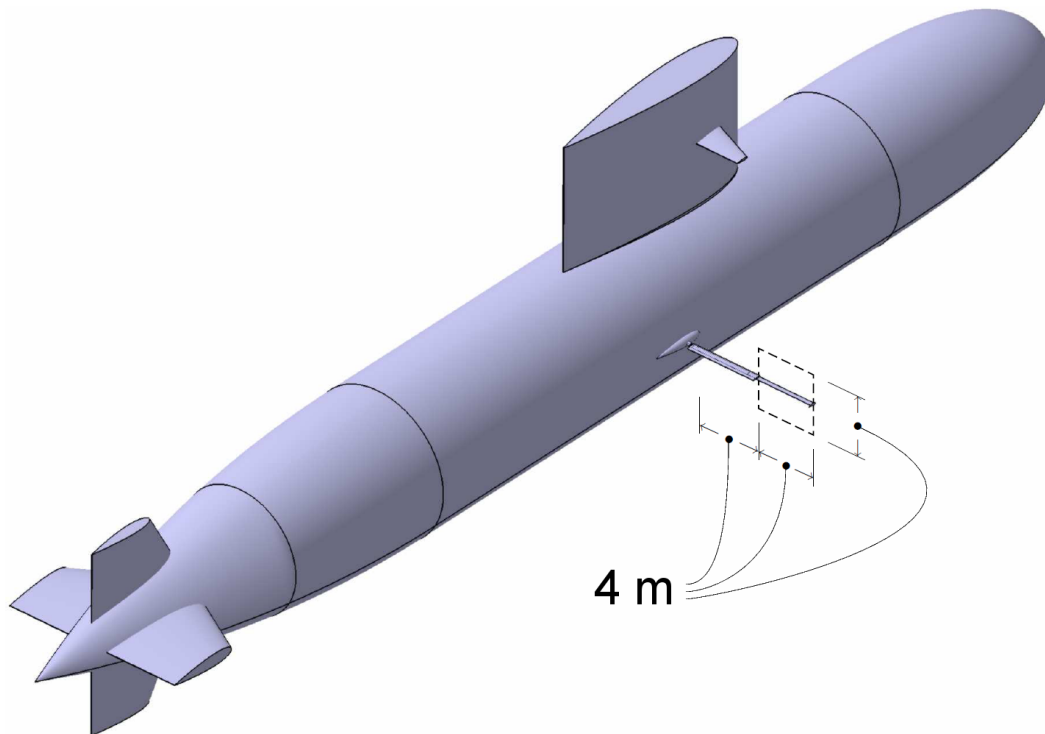

Figure 4: The docking envelope for the UUV during Stage 2 is a 4m×4m×10m box.

The revolute joint is passive because the docking mechanism is hydrodynamically actuated about this degree of freedom.

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That is, the first link has a foil shaped fairing which can be actively pitched, independently of and about the mechanism's first link. This causes lift and drag forces that actuate the passive revolute joint. By using hydrodynamic actuation instead of some mechanical actuation, the joint and docking mechanism package can be kept much more compact; the power required to actuate the mechanism is extracted hydrodynamically from the onset flow imposed by the submarine's forward motion.

The wing section is a symmetrical NACA type airfoil, it has a span of 4m and chord length of 1m. The prismatic link, likely to also be faired but assumed to be cylindrical here, can extend to a span of 4 m, as shown in Figure 5. At the end of the prismatic link is an end-effector which is not modelled here but would be a mechanism used to grasp the UUV.
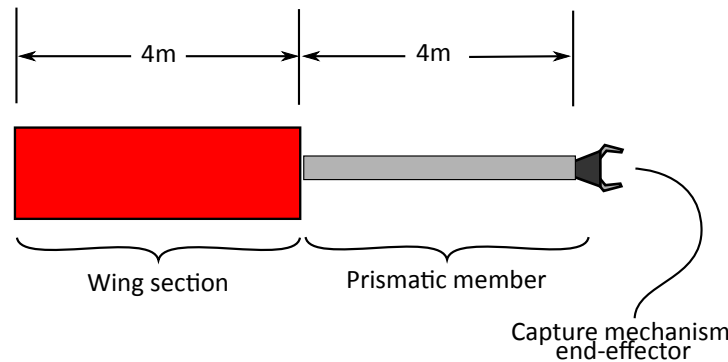

Figure 5: Docking mechanism dimensions.

2.4 Docking procedure

2.4.1 Overview

The docking procedure consists of two stages: the homing stage and the docking stage. During both stages, the submarine will attempt to hold its depth and heading constant while under environmental loading from the waves.

2.4.2 Stage 1: homing

The docking simulation begins assuming that the UUV has completed its mission and is loitering at the pre-determined rendez-vous location. The submarine has approached the rendez-vous location and is within 1 km of the UUV. They have exchanged recognition signals (handshaking) which has triggered the UUV and submarine to enter stage 1 of the docking procedure. The submarine communicates to the UUV homing strategy parameters. This includes the heading at which the docking occurs.

When stage 1 begins, the submarine has entered Steady Flight mode, described in Section 3.3.2, where it will try to hold a constant depth, speed, and heading; these will be held for the remainder of the simulation. In reality, the submarine will probably be controlled by its auto-depth and auto-heading autopilots while the operators retain control over speed and will be able to adjust forward speed to increase or decrease the docking time as the situation dictates (within the limits of the docking strategy).

The UUV on the other hand, has entered Homing mode and will attempt to home in on the submarine using a pair of PSSs.

A description of the homing strategy is described in detail in Section 3.3.3 and a description of the PSSs can be found in Section 3.5. At the same time, the submarine uses its superior speed to help close the distance between itself and the UUV. The objective of Stage 1 is to guide the UUV to the docking envelope; a space approximately 4m x 4m x 10m fore of the docking mechanism for a side capture method. Other capture methods may be considered in the future. The envelope is offset from the hull of the submarine by 4 m as shown in Figure 4 to provide some separation between the UUV and submarine and prevent any collisions.

When the UUV nears the active dock, the intermediate range EM PSS begins to offer better accuracy than the acoustic PSS. Sensor fusion between the acoustic and the intermediate range EM PSS will manage the differing levels of accuracy between the sensors and provide an estimate of relative position of the target.

When the UUV enters the docking envelope, and is in range of the optical or short range EM PSS located on the active docking mechanism, the active dock communicates with the UUV instructing it that stage 2 has begun.

2.4.3 Stage 2: capture

When both vehicles have entered stage 2, the UUV switches from Homing Mode to Steady Flight Mode and maintains a constant speed, heading and depth, while listening for and implementing commands from the submarine's docking control system (MDC). The dock will send periodic course corrections to the UUV to ensure it remains within the docking envelope.

The UUV will adjust its velocity to slip into the workspace of the active docking mechanism. The UUV's speed is commanded by the MDC and set to be proportional to the distance between the UUV and the plane of actuation such that when capture occurs, the UUV and the submarine are travelling at practically the same speed.

The docking mechanism uses its PSS to determine the relative position of the UUV and actuates itself to ensure its end effector matches the UUV's position in a plane transverse to the longitudinal axis of the submarine. Stage 2 is complete when the UUV slips past the dock's plane of actuation, and the dock's end-effector makes contact with the UUV, capturing it. Stage 2 also ends if the UUV failed to meet the target by any number of potential failure scenarios.

2.4.4 Docking failure

There are numerous modes in which a docking attempt would be considered a failure. Here is a short, non-exhaustive list of possible modes of failure:

- If the UUV collided with the submarine or the docking arm.

- If the UUV is unable to complete stage 1.

- If the UUV leaves the docking envelope during stage 2 and the docking mechanism loses position lock.

- If the UUV fails to connect with the capture mechanism on the docking arm.

Simulation complexity is being built up in stages. Methods of docking failure detection have not yet been considered and will be addressed at a later date. A capability to handle the complex navigational decision making required to abort a docking

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procedure due to failure and make further docking attempts will be developed by DRDC likely using MOOS-IvP [3], a vehicle autonomy software framework.

2.5 Control system modelling

To automate the docking process, a number of control systems are required. These control systems consist of autopilots, docking control systems and various sensors.

Both the UUV and submarine have their own autopilots (motion control systems). These are described in detail in Section 3. These autopilots are used to control the speed, depth, and heading of the vehicles. Both the submarine and the UUV would typically have a set of internal navigational sensors, such as those presented in Table 1, to assist in navigation and automatic control. These sensors would provide information about the state of the vehicles including their position, orientation, velocity, and acceleration.

Sensor type	Measure states
IMU	yaw, pitch, roll, yaw rate, pitch rate, roll rate, surge accel., sway accel., heave accel.
altimeter	distance from sea floor.
depth sensor	distance to ocean surface.
magnetometer (compass)	heading.
doppler velocity log	velocity relative to ground.
acoustic current doppler profiler	velocity relative to fluid.
global positioning system	longitude and latitude.

Table 1: A list of common sensors found on UUVs and submarines.

The docking control systems are separate control systems from the vehicles' autopilots. They are responsible for managing the docking procedure and will supply the autopilots with any information necessary for the vehicles to guide themselves through the docking procedure. The two vehicles have their own docking control systems. The submarine has the master docking controller (MDC) while the UUV has the UUV docking controller (UDC). Both the UDC and the MDC have PSSs which provide their respective docking controllers with positioning information.

The PSSs consists of both a source that emits a signal and a sensor which senses the signal. The system is used to detect the relative positions of the other vehicle. For simplicity, they are currently modelled to be statistically characteristic of their real counterparts rather than directly modelling the physics of how they operate. When available, detailed and high-fidelity sensor models can be added as needed to build up simulation complexity and fidelity. The PSS models are discussed in detail in Section 3.5. Figure 6 shows an overview of all of the components found on the two vessels for the scenario discussed here. The docking module is considered a single independent package that can be mounted to a submarine and can be controlled by the operators.

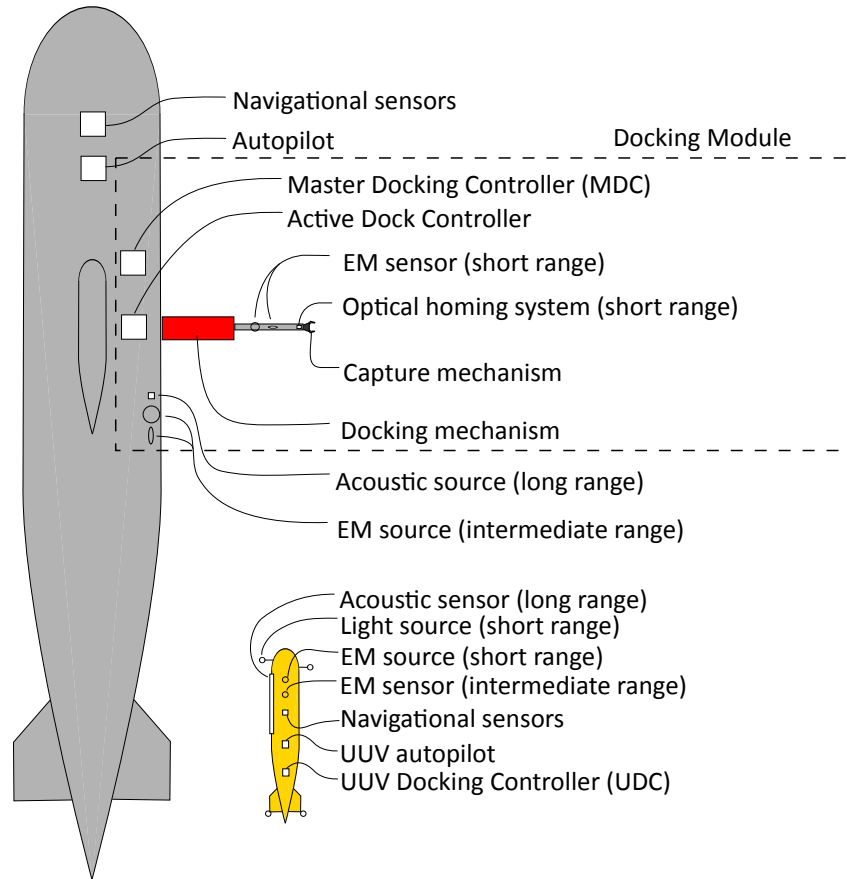| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 6: Some important control system components for UUV docking procedure.

2.5.1   UDC's positioning sensor systems

The UDC has a pair of PSSs used to determine the position of the submarine relative to the UUV during Stage 1 of the docking process. They consist of a long range acoustic system and an intermediate range EM system. Both provide information about the bearing and range of the submarine. Both systems have their sources located on the submarine, while the sensors are located on the UUV. The acoustic system has a functional range of 1-2 km, but has limited accuracy while the intermediate range EM system provides higher accuracy with a limited functional range of ≈50 m.

The acoustic PSS is modelled as an acoustic vector sensor; it determines the relative bearing of the submarine's docking envelope. The range of the docking envelope is modelled as an acoustic modem based ranging solution. Together, the acoustic modem ranging and acoustic vector sensor bearing signal can determine the location of the submarine in the horizontal plane and will be referred to together as the acoustic PSS. More detail on how the acoustic PSS is modelled is provided in Section 3.5.3 and 3.5.4.

Sensor fusion is employed to manage and reduce the error between the sensors. These position sensor systems are used to guide the UUV through stage 1 of the docking procedure. This relative position information is fed to the UDC to allow it to

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home in on its target, the docking envelope.

2.5.2 MDC's positioning sensor systems

The MDC, part of the docking module and mounted to the submarine (see Figure 6), also has a pair of PSSs. These are used to determine the position of the UUV relative to the dock during Stage 2 of the docking process. The first PSS is an EM based system with sensors mounted on the docking mechanism, they sense a signal from a weak (short-range) EM source mounted on the UUV. It has a functional range of about 50 m and can provide relative Cartesian position and potentially orientation (6 DOF).

In addition to the EM PSS, the docking module also makes use of an optical PSS. The optical positioning systems's sensor, a camera, is also mounted near the capture mechanism on the docking arm mechanism. It senses one or more light sources mounted on the UUV. It has a functional range of about 10 m and can also provide 6 DOF position. The relative position information will be used by the MDC to guide the docking arm mechanism through space to track and capture the UUV.

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3 Control systems

3.1 Introduction to marine vehicle control

It's important to consider the type of marine vehicle being controlled when designing their control systems. Controlling a surface-based marine vehicle is different than controlling a submerged vehicle because their workspaces are different.

Both types of marine vehicles have an $n = 6$ DOF configuration space, however most surface vehicles only have an $m = 2$ DOF workspace (surge, yaw) while submerged vehicles such as submarines tend to have $m = 3$ DOF workspaces (surge, pitch, yaw) or $m = 4$ DOF workspaces (surge, pitch, depth, yaw). The configuration space of a marine vehicle for control is the n dimensions of achievable positions/orientation for the vehicle, the vehicle motion degrees of freedom. It's workspace dimensions, m, is a reduced set of degrees of freedom which are actively controllable. The workspace must have an equal or less number of DOF than the configuration space.

Detailed descriptions of configuration spaces and workspaces can be found in [4]. This work only considers neutrally buoyant submerged marine vehicles that are stable in roll with $m = 4$ DOF workspace (surge, pitch, yaw, depth). The submarine has $r = 4$ independently controlled actuators (thruster, stern planes, bow planes, rudders). The UUV has $r = 3$ independently controller actuators (thruster, stern planes, rudder planes). This results in fully actuated $r >= m$ and underactuated marine vehicles since $r < m$ respectively.

3.2 Autopilots

Most vehicle motion control systems consist of three sub-systems; the guidance system, the navigation system and the control system [4], see Figure 7. These guidance, navigation, and control systems form what is often called an autopilot.

The vehicle's actuators, control surfaces, or thrusters generally also have their own individual controllers which take, as input, the desired state of the actuator from the autopilot's control system and responds to achieve them. It drives the actuator to achieve its desired state in a controlled fashion. In this work, the dynamic behaviour of the actuators and their controllers are modelled using a 2nd order transient response model [5].

Both the UUV and the submarine have their own autopilots. The navigation system uses sensor readings, such as from an inertial navigation system (INS), to help determine the vehicle's actual state: position, orientation, velocities and accelerations. The guidance system determines the desired state (position and velocity) of a vehicle given a particular control objective. Some possible control objectives may be setpoint regulation, trajectory tracking or path-following. This desired state is fed to the control system which determines the control action required to achieve it given the vehicle's actual state as determined by the navigation system.

The autopilot's Guidance system is discussed in detail in Section 3.3, while its Control system is discussed in Section 3.4.

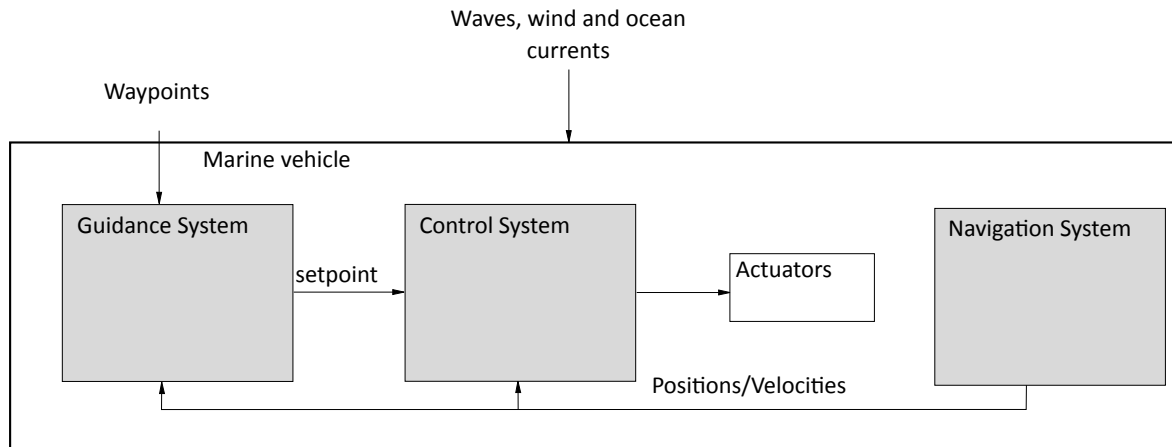| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 7: Idealized signal flow diagram of a GNC motion control system (Guidance/Navigation/Control). This figure is an adaptation from [4].

3.3 Guidance system block

3.3.1 Overview

There are three notable guidance routine classifications [4]:

1. Setpoint regulation - a desired state is chosen to be constant which the vehicle attempts to achieve. Setpoints can be altered over the course of the simulation in order to achieve mission objectives.

2. Trajectory tracking - forces the vehicle to track a smooth time-varying trajectory defined as a function of time $\mathbf{y}_d(t)$. The desired trajectory $\mathbf{y}_d(t)$ defines the desired vehicle state as a function of time. Feasible trajectories are generated using suitable reference models.

3. Path following - is similar to trajectory tracking except the vehicle is not constrained by time. The vehicle is only required to follow the path.

Also available are target tracking methods which are designed for tracking targets. This work focuses on target tracking methods, here a form of "Setpoint regulation". Path following and trajectory tracking methods are not considered by this work.

Setpoint regulation is required to allow the vehicles to achieve and maintain some desired state. This is something both the submarine and UUV are required to do. During stage 1 of the docking procedure, the UUV uses target tracking to allow the UUV to home in on the submarine. For this work, a constant bearing homing method was chosen to help guide the UUV to the docking envelope. More guidance routines may be required and implemented in the future as the complexity and scope of the simulation is increased. Particularly, guidance routines for handling remedial actions for docking failures will eventually be required.

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3.3.2 Steady Flight mode (Setpoint regulation)

Steady Flight Mode is a mode where the vehicle tries to maintain some desired heading, depth and speed. This is accomplished by passing in a constant desired set point to the control system block. The control system block will then handle achieving this target state. The submarine will be in Steady Flight mode for the entire duration of the simulation while the UUV will only enter Steady Flight mode during stage 2. For stage 2, the MDC will send periodic commands to the UUV's Docking Controller to update the Steady Flight mode setpoint and ensure the UUV remains in the flight envelope. These setpoint updates will be low frequency events.

3.3.3 Constant Bearing (CB)

This constant bearing homing strategy allows the UUV to travel at a lower velocity than the submarine conserving its remaining power reserves as much as possible while the submarine can take advantage of its large energy stores to travel at a faster speed to close the distance between the vehicles.

The constant bearing homing method described here was developed by DRDC and implemented/tested in the simulation software by DSA. The method is used to guide the UUV to the docking envelope during stage 1 of the docking procedure. Because the UUV is at the end of its mission and its energy reserves are likely depleted, the submarine will be the one expending energy to catch up to the UUV rather than vice versa.

The method begins with the UUV loitering at the rendez-vous location while sending occasional covert homing beacon signal for the submarine to locate it. The submarine approaches the rendez-vous location and determines the relative bearing of the UUV by using the covert acoustic homing beacon signal.

When the submarine is in a favorable position relative to the UUV, about 1 km away and heading towards it, handshaking occurs between the vehicles confirming the beginning of stage 1 of the docking procedure. The submarine instructs the UUV, at some distance ahead, to proceed forward at some constant desired depth, heading and speed. The submarine begins transmitting a simple spread spectrum acoustic signal for the UUV to home in on using its acoustic vector and acoustic ranging sensors.

The submarine will need to ensure it is maintaining the same depth and heading as commanded of the UUV and should proceed forward at a speed of $\mathbf{v}_{sub}$. The submarine's speed is faster than was commanded of the UUV in order to close the distance between the two. The submarine will keep a track parallel and offset to the UUV by some amount as shown Figure 8.

The submarine closes the distance between itself and the UUV, which is traveling at a lower speed ($\mathbf{v}_{UUV}$). During this time, the UUV is using its acoustic vector sensor to determine the relative bearing, α, of the submarine relative to the UUV's commanded heading. The relative bearing of the submarine will be reducing with time as the submarine catches up. Eventually, α will become equal or less than some predefined optimal angle α_i, a parameter sent by the submarine to the UUV at the start of stage 1.

The UUV then alters its heading to an angle ($\beta = \alpha_i - \gamma$), relative to the commanded heading, to travel towards the rendez-vous point. Technically, up until the point where the UUV altered its course, the submarine was free to travel at any speed, taking as long or as short of a time as necessary to close the distance between the two. However, the submarine will reduce its speed to the predetermined docking speed $\mathbf{v}_{sub}$ prior to the point where the UUV alters its heading.

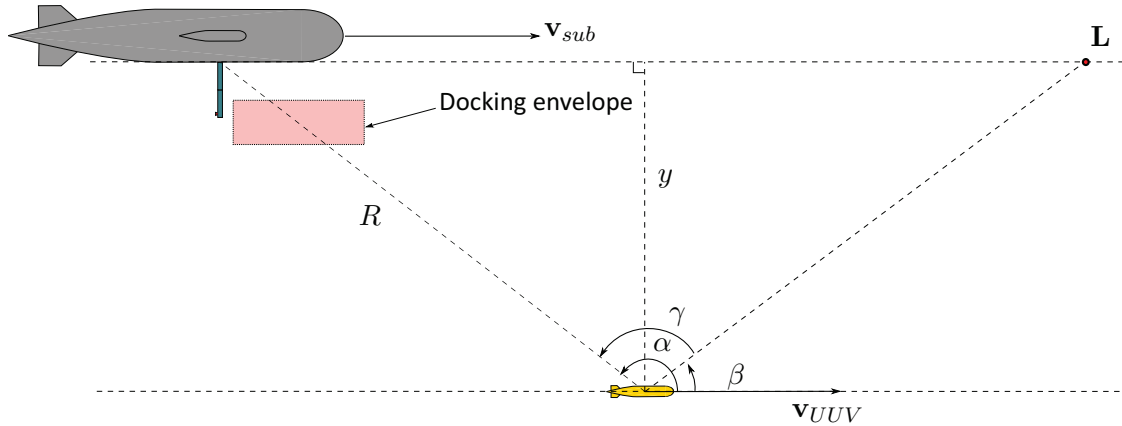| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 8: A plan view of stage 1 of the docking procedure, showing the geometry of the constant bearing homing method.

The UUV will maintain its heading, β, and adjust its forward speed in order to ensure a constant relative bearing (α), between the submarine and the UUV's commanded heading, is maintained. The UUV will intercept the submarine at point $\mathbf{L}$. The submarine will reach point $\mathbf{L}$ after t seconds from the instant where the UUV begins altering its heading. The UUV will take the same amount of time (t) to reach $\mathbf{L}$ but along the β heading as shown in Figure 8. The relationship between the submarine and UUV velocities can be described using the Law of Sines:

$$\mathbf{v}_{sub} = \frac{sin(\gamma)}{sin(\alpha_i)}\mathbf{v}_{UUV} \tag{1}$$

The angle γ is the predetermined bearing required to initiate the homing maneuver of the UUV. Ideally, γ should be chosen near $\frac{\pi}{2}$. This relative bearing angle provides the optimal accuracy in the bearing measurement of the acoustic vector sensor. Thus, $\frac{\mathbf{v}_{sub}}{\mathbf{v}_{UUV}} \approx \frac{1}{sin(\alpha_i)}$ and arbitrarily large $\frac{\mathbf{v}_{sub}}{\mathbf{v}_{UUV}}$ magnitudes can be attained as α_i approaches π. This is demonstrated by the red line in Figure 9. The limit that $\mathbf{v}_{sub}$ must be greater than $\mathbf{v}_{UUV}$ imposes that α_i must be greater than γ. This limit is illustrated by the blue line in the same Figure.

Using this strategy, the UUV is able to close the distance between itself and the submarine, eventually meeting at $\mathbf{L}$.

Assume that initially, $y = 200$ m (see Figure 8), $V_{UUV} = 1$ m/s, and the docking speed is 2 m/s. By restricting γ to $\frac{\pi}{2}$ results in $\alpha_i = \frac{5}{6}\pi$. The submarine will have to ensure that when it is around 400 m aft of the UUV that its speed is reduced to about 2 m/s. When the UUV detects that $\alpha = \alpha_i$ it will turn towards the submarine, continuously monitor α, and adjust its speed to maintain $\alpha = \alpha_i$. At the same time, it will be adjusting its heading to keep $\gamma \approx \frac{\pi}{2}$ constant. If $\gamma \approx \frac{\pi}{2}$, then equation 1 is insensitive to perturbations in γ and there should be minimal conflict between speed and heading adjustments.

In order to smooth the approach of the UUV into the docking envelope, the UUV's heading is commanded to start and match that of the submarine's once it reaches a predefine lateral distance (y_{UL}) from the submarine, proportionally reducing β as the UUV gets laterally closer to the submarine. This allows the UUV to pull along side the submarine in parallel. Another predefined lateral distance is the docking envelope boundary defined by y_{LL}. Once the UUV reaches this lateral distance, the commanded heading is equal to the heading of the submarine. The UUV's heading relative to the commanded heading,

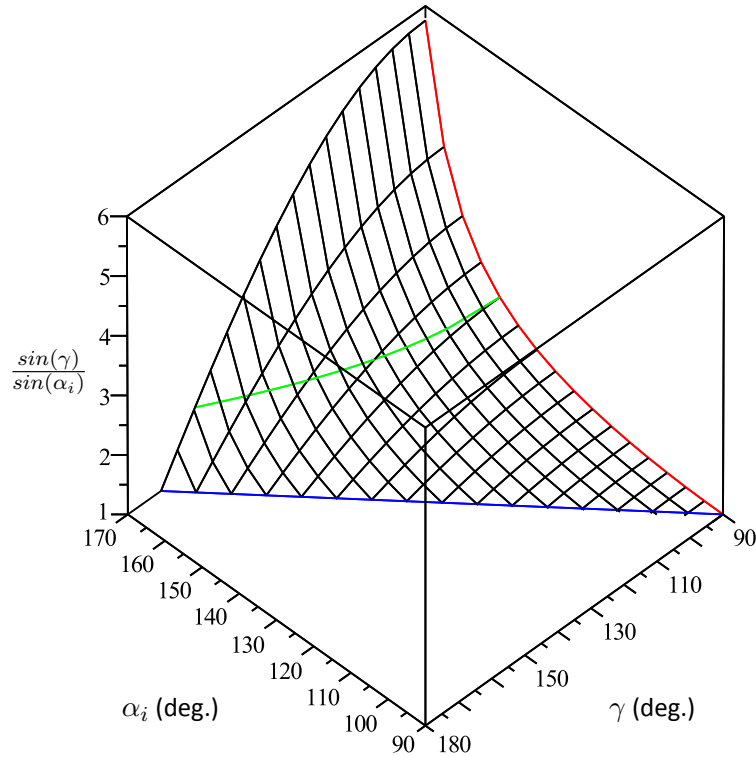| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 9: A surface plot of the speed ratio between the UUV and submarine as a function of α and γ. The interception surface is symmetric about $\gamma = 90$ degrees. The green line shows possible combinations of α and γ that produce a speed ratio of 2.

β, is thus set according to:

$$
\beta = \begin{cases} 0 & if\ \alpha > \alpha_i \\ \alpha_i - \gamma & else\ if\ y > y_{UL} \\ (\alpha_i - \gamma)(\frac{y - y_{LL}}{y_{UL} - y_{LL}}) & if\ y < y_{UL} \end{cases} \tag{2}
$$

The locations of the sources for the acoustic and intermediate range EM PSS are located on the submarine such that the path of the UUV passes into the docking envelope during the constant bearing homing routine.

When the UUV enters the docking envelope and the Docking Module's PSSs can sense the UUV, the docking procedure switches into Stage 2. Note that with this homing strategy, the UUV is entering the docking envelope on a heading parallel to that of the submarine to avoid impacting the submarine.

3.4   Control system block

The control system block shown in Figure 7 takes a desired state as input signals from the guidance system and the actual state as input signal from the navigation system. From these signals, it computes the vehicle appendage (the control surfaces and thrusters) states required to achieve the desired vehicle state. Modern control systems can be based on a variety of control schemes such as Proportional-Integral-Derivative (PID) control, model predictive control (MPC), H_∞ control, fuzzy systems,

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neural networks, etc. For this work, only a PID control system block is considered to maintain simplicity. PID control schemes are among the most widely used forms of control [4].

A regular single-input/single-output PID control equation takes the form of

$$s_o(t) = G_P e(t) + G_I \sqrt{\int_0^t e(t)dt} + G_D \dot{e}(t) \tag{3}$$

where

$$e(t) = s_i(t) - s_t \tag{4}$$

is the error at time t between the actual state signal $s_i(t)$ and the target or setpoint signal s_t, G_P is the proportional gain, G_I is the integral gain, G_D is the derivative gain.

For multi-input/multi-output PID control, the PID control equation can be converted to a set of linear equations with N_i input signals and N_o output signals. The N_i input signals are placed in a length N_i vector $\mathbf{s}_i(t)$ which correspond to the N_i setpoint signals in the length N_i setpoint vector $\mathbf{s}_t$. The N_o output signals are placed in a length N_o vector $\mathbf{s}_o(t)$. The error signals for the controller, $\mathbf{e}(t)$, is also a length N_i vector which holds the error between the input signal and the desired target set points for said input signals. The control equations then take the following form:

$$\mathbf{s}_o(t) = \mathbf{G}_P \mathbf{e}(t) + \mathbf{G}_I \sqrt{\int \mathbf{e}(t)dt} + \mathbf{G}_D \dot{\mathbf{e}}(t) \tag{5}$$

where

$$\mathbf{e}(t) = \mathbf{s}_i(t) - \mathbf{s}_t \tag{6}$$

Because there are N_i input signals and N_o output signals, $\mathbf{G}_P$, $\mathbf{G}_I$ and $\mathbf{G}_D$ must therefore be $N_i \times N_o$ sized matrices containing gains which map the influence of an error signal to an output signal. Figure 10 shows a diagram of a MIMO PID controller block, showing the input signals and its related setpoints as well as the resulting output signals. Such a MIMO control scheme can effectively ensure a marine vehicle maintains its desired (setpoints) pitch, speed, depth, and heading.

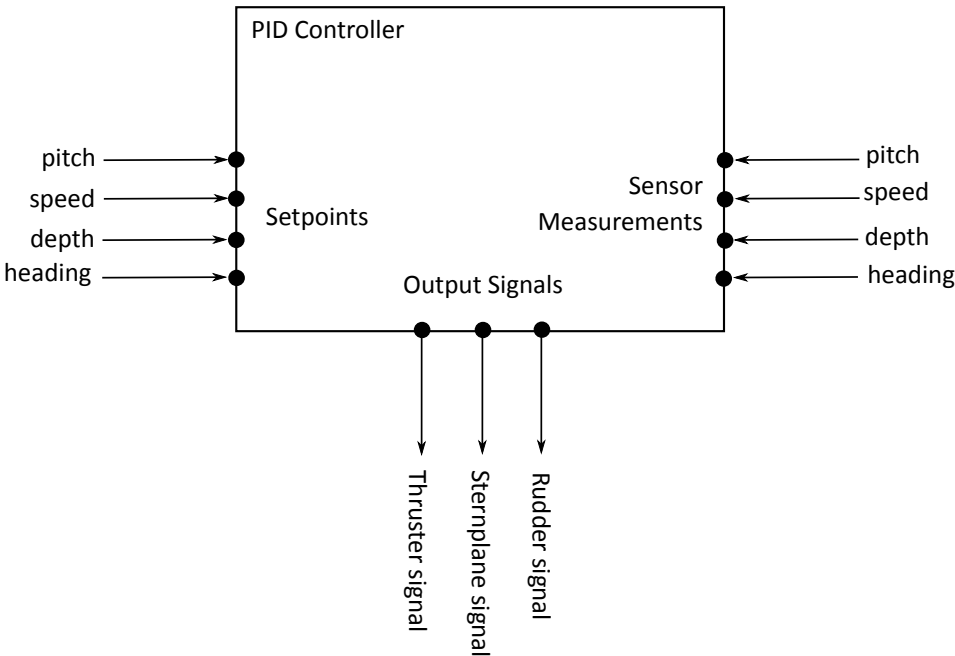| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 10: PID Controller flow chart showing the inputs, setpoints and outputs.

3.5   Sensors

3.5.1   Overview

The purpose of this simulation software is to determine the feasibility of docking strategies under various environmental loading conditions. To capture the statistical success rates of the docking procedure, the statistical behaviour of the sensors must be reasonably captured. This is important because motion control decisions are made based on sensor signals that are not perfect measurements. Sensors have measurement error: bias and noise.

An abstract sensor class is discussed in Section 3.5.2. It describes at a high level how the sensor models model error.

The 4 PSSs are described in Sections 3.5.3 to 3.5.6. The other sensors shown in Figures 29 and 30 such as the INS and manipulator sensors are considered to be ideal for the time being, or without error. Those sensors are briefly discussed in Section 3.5.7.

3.5.2   Abstract statistical sensor

A high level flow diagram showing how the error for all sensors are modelled is shown in Figure 11. The true state is known from the simulation state and is passed on to the error model. The sensor's error is determined as bias and random noise based on the "ideal measurement", environmental conditions, error model parameters, and even external controls. A normally distributed random number generator with a mean of zero is used to generate noise; the noise's standard deviation is a good measure of the noise level. The error bias and randomly generated noise values are then superimposed onto the

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ideal measurement signal. This final result, with error, is then passed out as the sensor's output.

Environmental conditions can affect the sensor's error. For example, an optical sensor's accuracy would be affected by the turbidity of the water. For acoustic sensors, environmental noise and signal reflections could cause error. For EM sensors, the background EM noise could cause error. The error model and its parameters will differ depending on the sensor type being modelled. However, they follow the flow diagram presented in Figure 11.
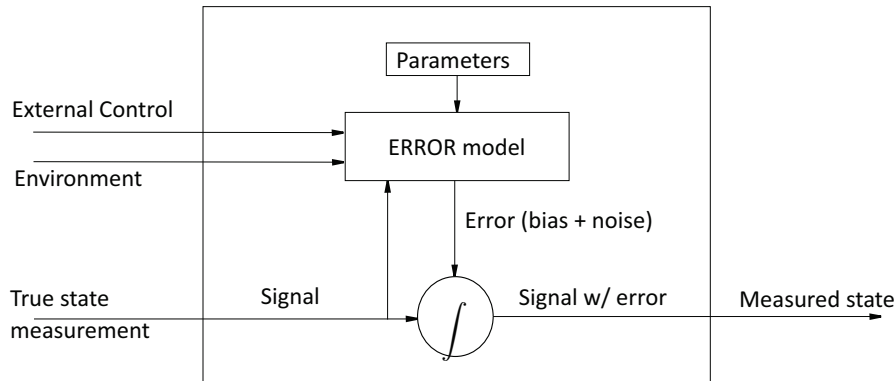

Figure 11: Abstract sensor flow diagram.

3.5.3 Acoustic vector sensor

3.5.3.1 overview

An acoustic vector PSS was chosen by DRDC to allow the UUV to home in on the submarine using its constant bearing homing strategy. The sensor consists of a strip of individual acoustic sensors or pickups, as shown in Figure 13 a). The bearing of the source will likely be estimated using a method based on or similar to [6]. However, until details of the sensor are available, a simplified sensor model was developed for this work. The vector sensor's reference frame, relative to which the bearing is measure is illustrated in Figure 12.
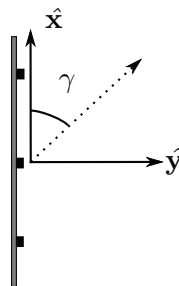

Figure 12: The reference frame for the acoustic vector PSS' sensor.

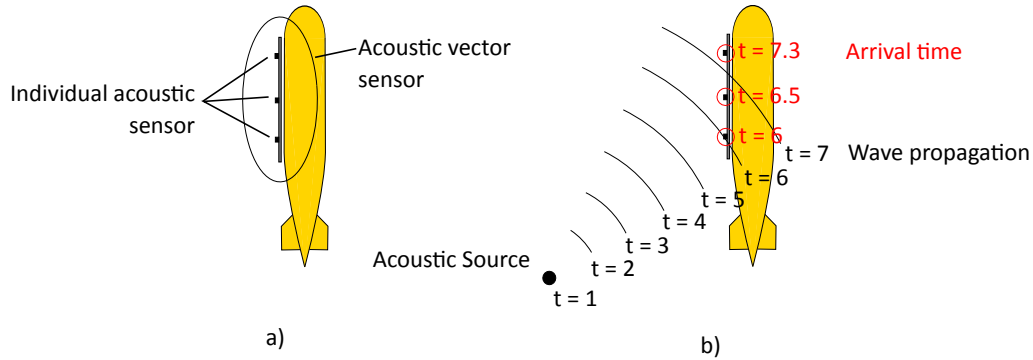| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 13: a) Acoustic vector sensor as a strip of individual acoustic sensors. b) Wave arrival time difference between individual acoustic sensors used to determine the bearing of the source.

3.5.3.2 Bearing error from signal phase measurement error

The signal, a wave, will be received by each individual pickup at any single instant in time at different phases. This might be better understood by visualising the phase as the different time of arrivals of the sinusoidal peaks of the signal as illustrated in Figure 13 b). Using the speed of sound in the fluid, the distance between the individual sensors in the strip and the differences in arrival times of the signal peaks between the sensors (different phases), the relative bearing of the source can be determined.

The acoustic source on the submarine sends a signal which travels at a speed V_s, the speed of sound in the fluid, towards the acoustic vector sensor. The difference in arrival time of the signal's wave front between the individual sensors, δt is:

$$\delta t = d \cos(\gamma)/V_s \tag{7}$$

$$= \frac{\phi_d}{\omega} \tag{8}$$

where γ is the bearing of the source relative to the acoustic vector sensor, or the propagation direction of the signal relative to the sensor strip, as shown in Figure 14, d is the distance between the individual sensors in the strip, ω is the signal's frequency and ϕ_d is the instantaneous phase difference of the signal between the two sensors. The relative bearing of the source, γ, can be determined in terms of the speed of sound, the difference in arrival time δt of the signal and the distance between the sensors d as:

$$\gamma = \arccos \frac{V_s \delta t}{d} \tag{9}$$

By combining equations 8 and 9, γ becomes:

$$\gamma = \arccos \frac{V_s \phi_d}{\omega d} \tag{10}$$

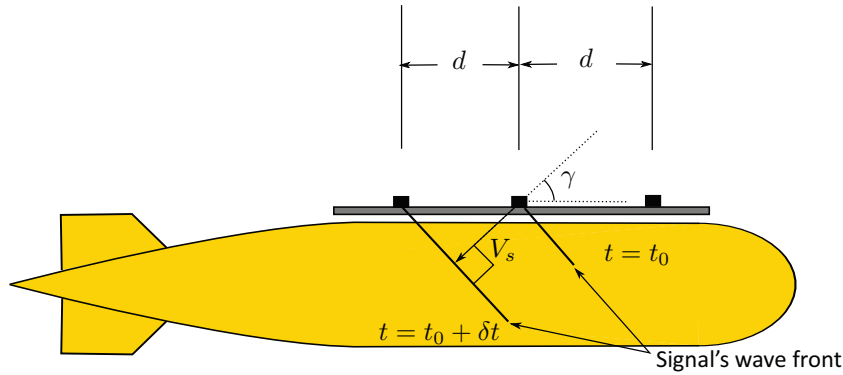| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 14: A diagram demonstrating how the source's bearing γ relative to the sensor strip is determined.

where ω is the signal's frequency. Or, by solving for the instantaneous phase difference ϕ_d of the acoustic wave between two sensors can defined as:

$$\phi_d = \frac{\omega d}{V_s} \cos(\gamma). \tag{11}$$

3.5.3.3 *Sensor error as a function of relative bearing*

Differentiating equation 10 with respect to time, the rate of change of the bearing measurement, γ, with respect to the relative arrival time is determined as:

$$\frac{\partial \gamma}{\partial \phi_d} = \frac{V_s}{\omega d} \frac{1}{1 - \frac{V_s^2 \phi_d^2}{\omega^2 d^2}} \tag{12}$$

$$= \frac{V_s}{\omega d \sin(\gamma)} \tag{13}$$

$$\tag{14}$$

The rate of change of the bearing with respect to phase measurement error $\frac{\partial \gamma}{\partial \phi_d}$ describes how the sensor's bearing measurement is affected by errors in phase measurement. The bearing sensitivity to phase measurement error is lowest at source bearings of 90 degrees.

Low signal to noise ratio, due to low signal strengths or high environmental noise, or long transmission distances, are likely to cause errors in signal phase. This would lead to large errors in bearing when the source has a bearing of away from 90 degrees. A plot of the normalised rate of change of the bearing with respect to phase measurement error $\frac{\hat{\partial} \gamma}{\partial \phi}$ is plotted against relative bearing in Figure 15. It is a plot of Equation 13 where V_s is 1484m/s and d is 0.5m. The sensor error is normalised by the error for a bearing of $\gamma = 90$ degrees: $\frac{\partial \gamma}{\partial \phi_d} = 2.9680e + 003$.

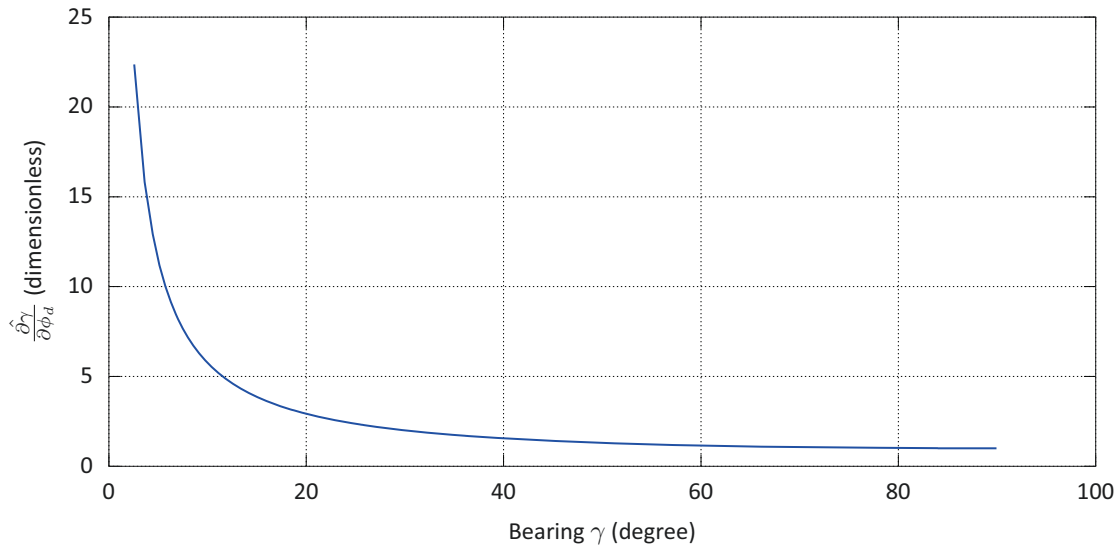| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 15: The sensor error, or the change of the bearing measurement with respect to a change phase measurement, plotted against the relative bearing of the signal's source.

3.5.3.4   Transmission losses

The signal to noise ratio is likely to have a strong impact on the error of the acoustic vector sensor. The signal begins at the source with a given intensity and power level. The intensity is the average amount of sonic energy transmitted per unit time through a unit area.

$$P = 4\pi r_s^2 I \tag{15}$$

where P is the power of the signal, and I is the signal's intensity at a distance r_s its source.

Because the signal wave propagates spherically, as shown in Figure 16, the amplitude of the wave will decrease as it propagates away from its source. Due to conservation of energy principles, the total power of the wave as it propagates out stays the same:

$$P = 4\pi r_o^2 I_o = 4\pi r_s^2 I_s \tag{16}$$

However since the surface area of a sphere increases quadradically with the radius, the intensity of the signal will decrease. The intensity of a signal at some distance r_s can be estimated if the intensity is known at some other distance:

$$I_s = I_o \Big) \frac{r_o^2}{r_s^2} \Big(\tag{17}$$

For spherical spreading, intensity is said to decrease as the inverse square of the range. Generally the intensity of the signal at the source, I_o, is defined at a unit range, $r_o = 1$ m, from the source. The transmission loss, expressed in Decibels (dB),

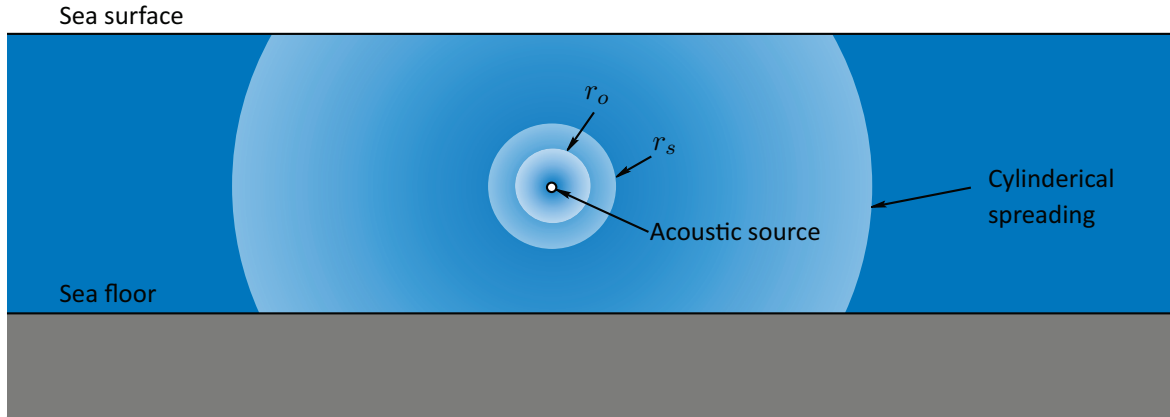| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Sea surface

Sea floor

Figure 16: A sound wave generated by a sound source underwater showing spherical spreading. Also shown are a unit sphere with radius r_o about which the source's power is defined and a sphere of radius r at which the sound wave's intensity is desired. Figure is an adaption from [http://www.dosits.org/science/advancedtopics/spreading/].

when recieved at some range r_s is then:

$$TL = -10 \log_{10} \left) \frac{I_s}{I_o} \left(= 10 \log_{10} r_s^2 \left(= 20 \log_{10} \left(r_s \right) \right. \tag{18}$$

That said, sound cannot propagate spherically forever since it will reach the bounds of its medium, the sea floor and surface. Beyond that range, limited by the sea floor and surface, the sound waves will propagate cylinderically. For the time being, cylinderical propagation is ignored until this level of detail is required.

From the sonar equation, the signal level at the receiver, RL, in dB is:

$$RL = SL - TL \tag{19}$$

where SL is the source's level at a unit range, r_o.

The ocean environment will have background noise present which will interfere with the ability to receive the acoustic source's signal. The noise level, NL varies with frequency as shown in Figure 17. The sensor is likely to operate at a frequency near 1500 kHz. For a sea state 6, this corresponds to environmental noise level of around 70 dB.

The signal to noise ratio, SNR(dB), in dB, at the receiver is:

$$SNR(dB) = SL - TL - NL \tag{20}$$

The non-logarithmic signal to noise ratio, SNR, is determined as:

$$SNR = 10^{\frac{SNR(dB)}{20}} \tag{21}$$

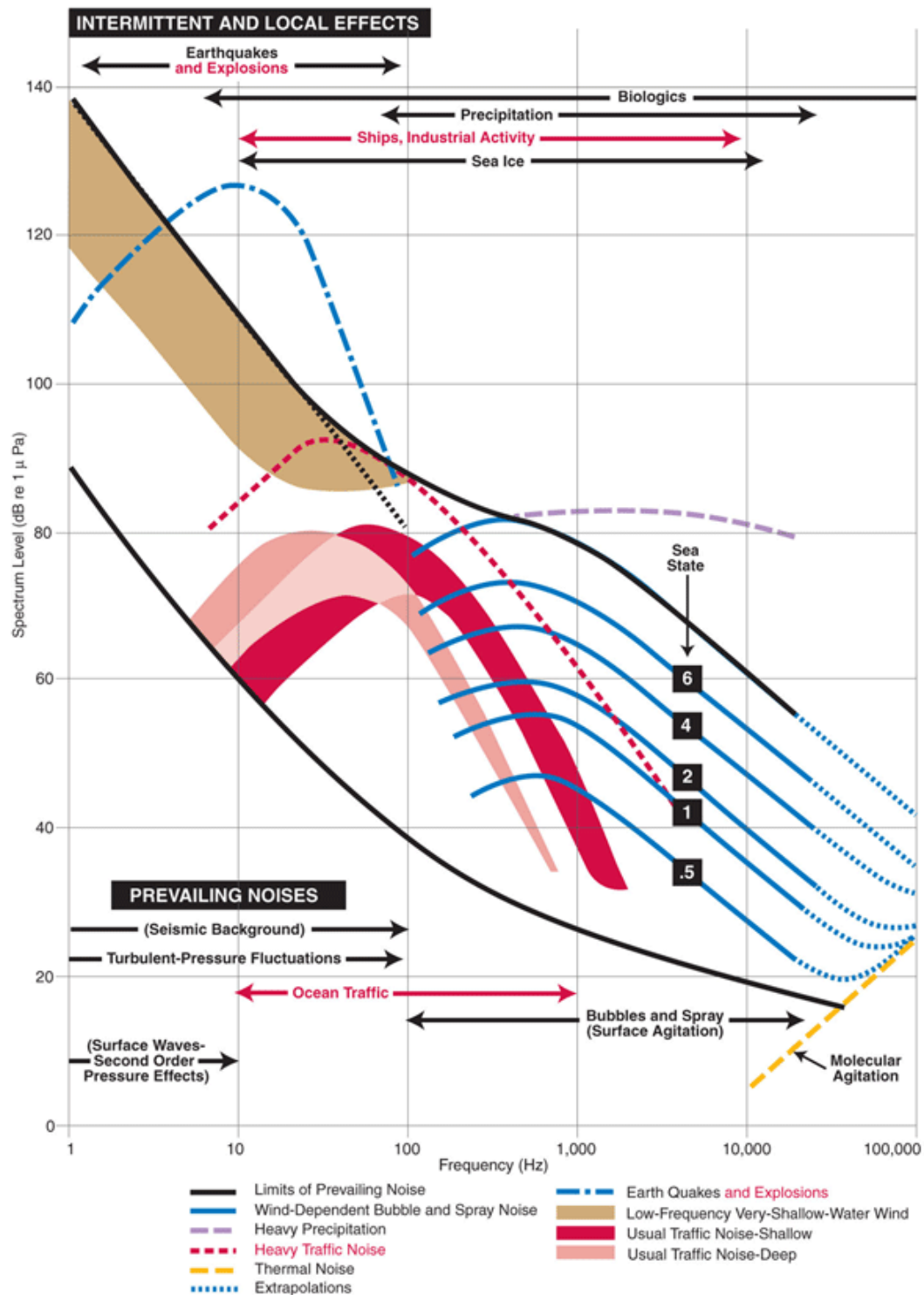| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 17: Sound levels of ocean background noises at different frequencies as measured by Wenz (1962). Figure is an adaptation from 2003, Ocean Noise and Marine Mammals, National Academy Press, Washington, D.C. [http://www.dosits.org/science/soundsinthesea/commonsounds/]

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3.5.3.5 Modelling error

The acoustic sensor models are under development. For the purposes of this work, DSA has implemented a simple sensor model that superimposes a normally distributed error on top of the ideal bearing measurement that is inversely proportional to the SNR and for the acoustic vector sensor also dependent on the bearing angle. This model captures the phenomenon of spherical spreading losses.

The error standard deviation, or error level, E, for the acoustic vector sensor, which will be superimposed onto the true relative bearing measurement as random noise, is:

$$E(R, \gamma) = \frac{k_r}{SNR} k_b \frac{\partial \hat{\gamma}}{\partial \phi_d} \tag{22}$$

$$= \frac{k_r}{10^{\frac{SL-TL-NL}{20}}} k_b \frac{\partial \hat{\gamma}}{\partial \phi_d} \tag{23}$$

$$= \frac{k_r}{10^{\frac{SL-20\log_{10}(R)-NL}{20}}} k_b \frac{V_s}{\omega d} \frac{1}{1 - \frac{V_s^2 \delta \phi_d^2}{d^2 \omega^2}} \tag{24}$$

$$\propto R \frac{\partial \hat{\gamma}}{\partial \phi_d} \tag{25}$$

where k_r is the sensitivity factor of the error to the SNR ratio with units of degrees and k_b is the error's bearing sensitivity factor. This produces an error level that grows linearly with range as shown in Figure 18 and also has decay in error with respect to relative bearing as shown in Figure 19. If the acoustic PSS' sensor is outside of the working range, R_{min} and R_{max}, of its source, the error level becomes ∞.
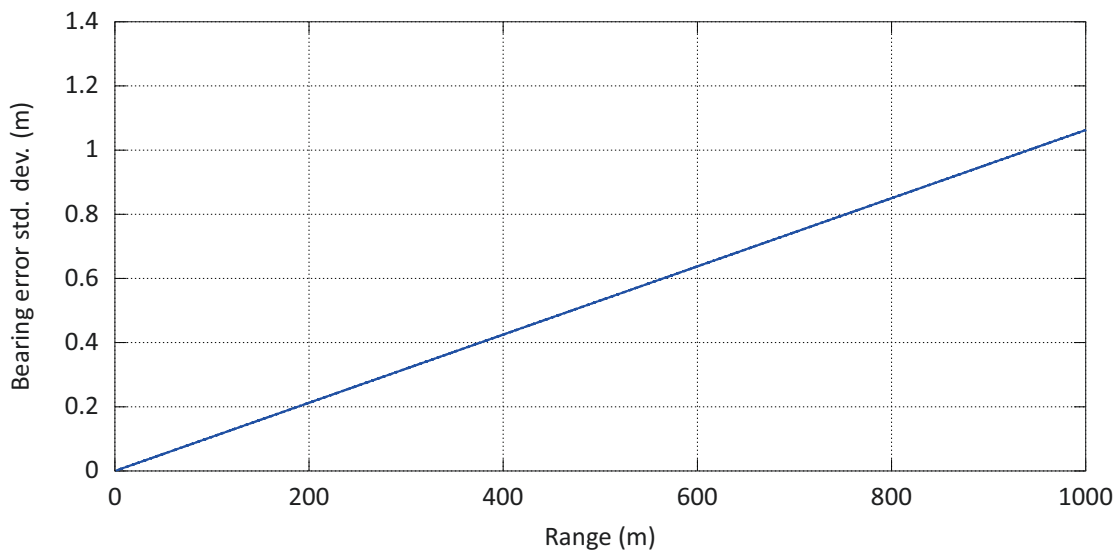

Figure 18: The error as a function of range for the acoustic vector sensor where $SL = 120$, $NL = 55$ and $k_r = 2$ degrees, $k_b = 2$ degrees and $\gamma = 90$. This is a plot of Equation 22.

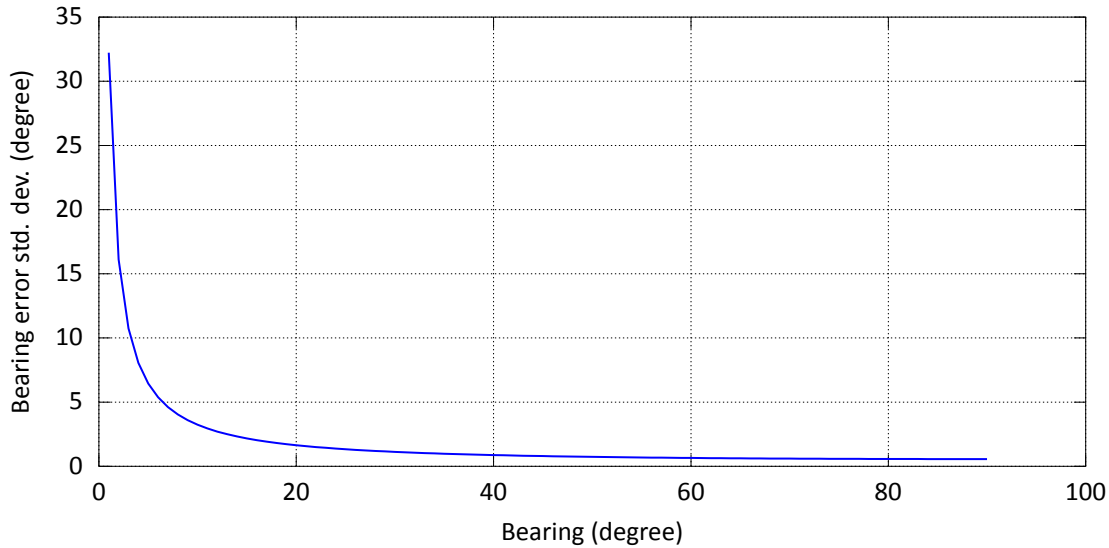| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 19: The error as a function of relative bearing for the acoustic vector sensor where $SL = 120$, $NL = 55$ and $k_r = 25$ degrees, $k_b = 1$ and $r_s = 500m$. This is a plot of Equation 22.

3.5.4 Acoustic Modem Ranging

Range information is required to support the chosen constant bearing homing strategy. Range information can be obtained through the use of acoustic modem ranging. This technique works by having the UUV's acoustic modem send a query signal to the submarine, which then sends a message back. The range can be determined as the total time required to retrieve the reply, minus some constant amount of time required for the submarine to process the request, all divided by the speed of sound in the fluid.

The acoustic signal will have spherical/cylindrical transmission losses and will similarly be affected by background noise as described in Section 3.5.3. Complete error modelling details for acoustic ranging await the results of DRDC trials. In the meantime, DSA has implemented a simple error model to attempt to capture the sensor error's dependence on range and environmental noise levels. The error in range measurement is modelled similarly to the acoustic vector sensor where the error standard deviation will be superimposed onto the true relative range measurement as random noise, is:

$$E(R) = k_r/SNR \tag{26}$$

$$= k_r/10^{\frac{SL-TL-NL}{20}} \tag{27}$$

$$= k_r/10^{\frac{SL-20\log_{10}(R)-NL}{20}} \tag{28}$$

$$\propto R \tag{29}$$

where k_r is the error's sensitivity to the SNR ratio with units of meters. This produces an error level that grows linearly with range as shown in Figure 20 for a $SL = 120$, $NL = 55$ and $k_r = 60$ meters. Similarly to the acoustic vector sensor, if the PSS's sensor is outside the working range, R_{min} and R_{max} of its source, the error level becomes ∞.

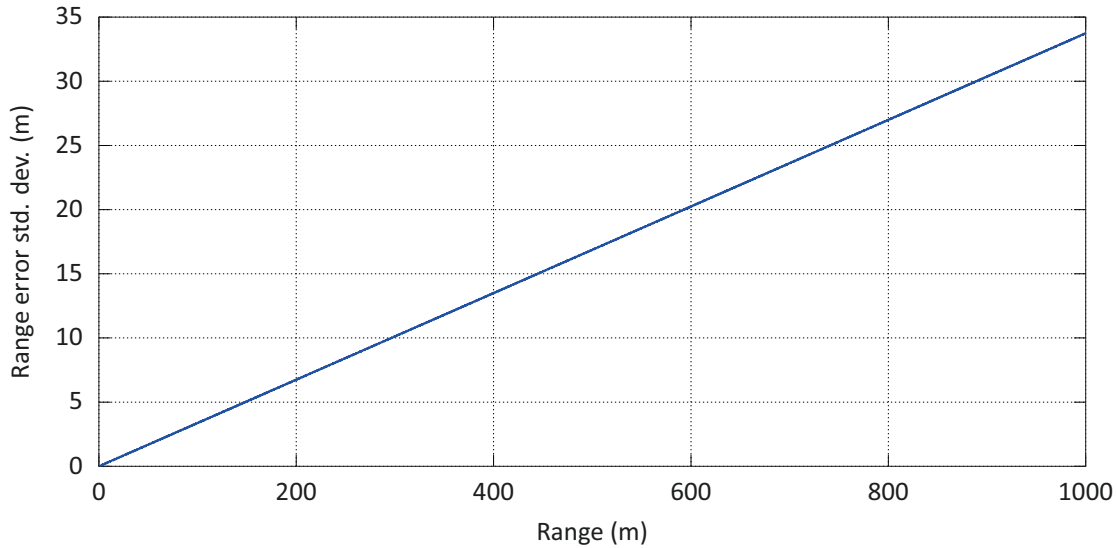| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 20: The range error as a function of range for the acoustic modem ranging system where $SL = 120$, $NL = 55$ and $k_r = 60$ meters. This is a plot of Equation 26.

3.5.5 EM positioning system

An EM PSS is being developed by DRDC. Until modelling details become available, DSA has implemented a simple EM sensor model as a place holder until a model is provided. The position error for the sensor is modelled as illustrated in Figure 21. The sensors have a minimum and maximum range, R_{min} and R_{max}, beyond which the location of the source cannot be determined. The error level would reach infinity. Within R_{min} and R_{max}, the error standard deviation is defined as a function of range as:

$$E(R) = \begin{cases} \infty, & \text{if } R < R_{min} \\ R\frac{dE(R)}{dR}, & \text{if } R_{min} <= R <= R_{max} \\ \infty, & \text{if } R > R_{max} \end{cases} \tag{30}$$

where R is the source's range from the sensor and $\frac{dE(R)}{dR}$ is the rate of change of error with respect to range. The error is modelled as normally distributed noise superimposed over the true relative Cartesian position as described in Section 3.5.2.

The simulation being developed here has two EM PSSs. They are currently being modelled identically though they will have different model parameters. The intermediate range EM PSS provides both bearing and range for stage 1 and will assist the acoustic PSS via sensor fusion. The short range EM PSS will provide 6 DOF relative Cartesian position for stage 2 and will assist the optical PSS via sensor fusion.

For the intermediate EM PSS, the source is located on the submarine while the sensor is located on the UUV. For the short range EM positioning system, the source is located on the UUV while the sensor is located on the docking arm next to the optical positioning system's sensor.

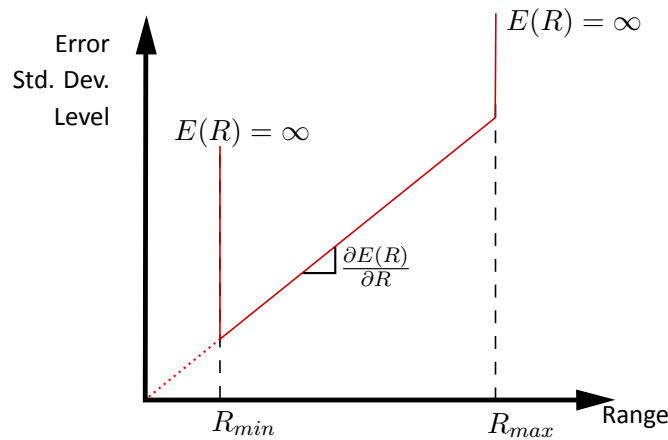| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 21: EM error model

3.5.6 Optical positioning system

This optical PSS consists of the sensor, which is a camera mounted to the docking arm, and a set of light sources which are mounted to the UUV. The optical PSS, along with the short-range electro-magnetic PSS, are used to aid with stage 2 of the docking process. A place-holder optical PSS error model was developed with DRDC. The error in the sensor is modelled similarly to the EM PSS with some differences. A higher fidelity optical sensor model will be implemented when it becomes available.

The sensor (camera) has a field of view and, similarly, the light source has a field of illumination. There are range limits on the field of view and field of illumination, as shown in Figure 22 a). The fields of view and illumination are rectangular as shown in Figure 22 b). The angle of the camera field of view is defined by the angles K_β and K_α while the light source's field of illumination is defined by the angles Ψ_β and Ψ_α. Both the camera and the light sources are facing forward along their local $\hat{x}$ axis as shown in Figure 22 a).

The optical PSS ensures that the camera can see the light source by using the relative bearing and azimuth angles between the camera and the light source, from the cameras point of view. If the light source is within the field of vision of the camera, it will then check the relative bearing and azimuth from the lights point of view. If both camera and light are in each other's respective fields, it can be said that the camera can sense the light source. The range limit R_{max} represents the furthest distance that the camera could see the light source in clear, dark water while the range limit R_{min} represents the minimum range which regardless of water quality, the camera will be able to see/detect the location of the light source.

A few optical sensor scenarios are illustrated in Figure 23. Scenario a) shows the light source beyond the vision of the camera and therefore the camera fails to detect the light source. In scenario b), the light source is within the 'vision cone' and range of the camera, however, the camera is not in the 'light cone' and therefore the camera fails to detect the light source. Scenario c) depicts detection of the light source by the camera. The camera's 'vision cone' contains the light source, the 'light cone' contains the camera, and the light source is within the maximum vision range of the camera.

Once the bearing and azimuth limit conditions are satisfied, the sensor's statistical error standard deviation is computed.

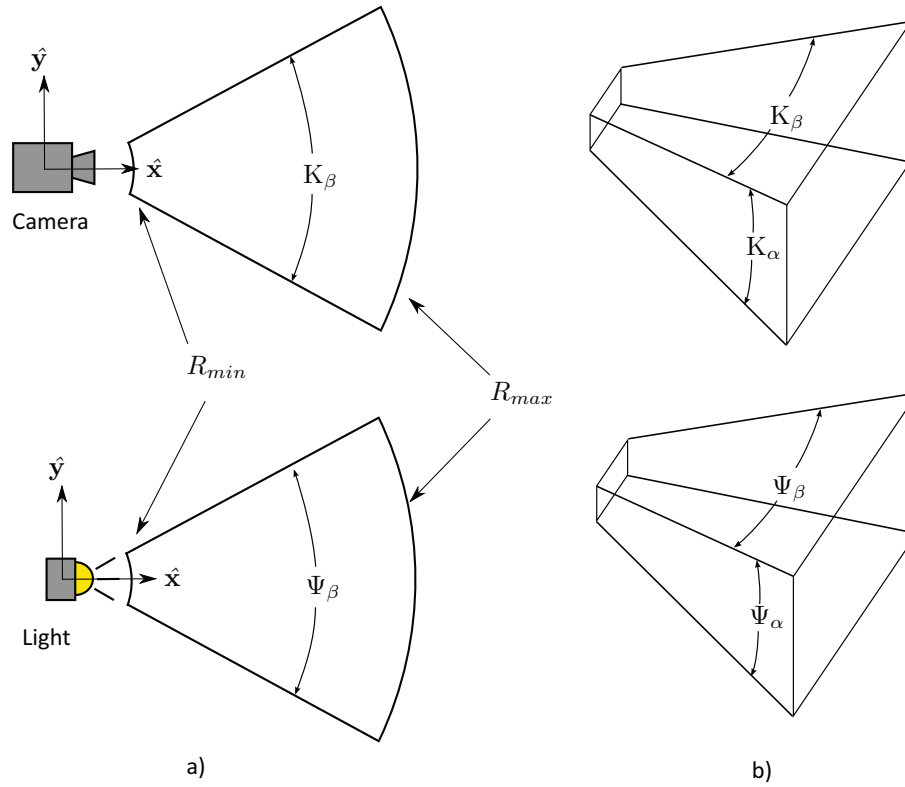| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 22: A diagram showing the camera and light source and some of the parameters that control the model. It's currently assumed that the vector s is parallel with $\hat{y}_{cg}$.

Like the EM sensor, the error is a function of range as shown in Figure 24. However the error as a function of range is defined a bit differently.

The error level for the optical sensor model, assuming the camera can see the light, is defined as:

$$E(R) = \begin{cases} \infty, & \text{if } R < R_{min} \\ E_{R_{max}} \frac{R}{R_{max|reduced}}, & \text{if } R_{min} <= R <= R_{max|reduced} \\ \infty, & \text{if } R > R_{max|reduced} \end{cases} \tag{31}$$

where $E_{R_{max}}$ is the error level at the maximum working range in clear, dark water. The furthest distance that the camera could see the lights is reduced based on the water's turbidity. The maximum detectable range of the camera R_{max} is reduce,

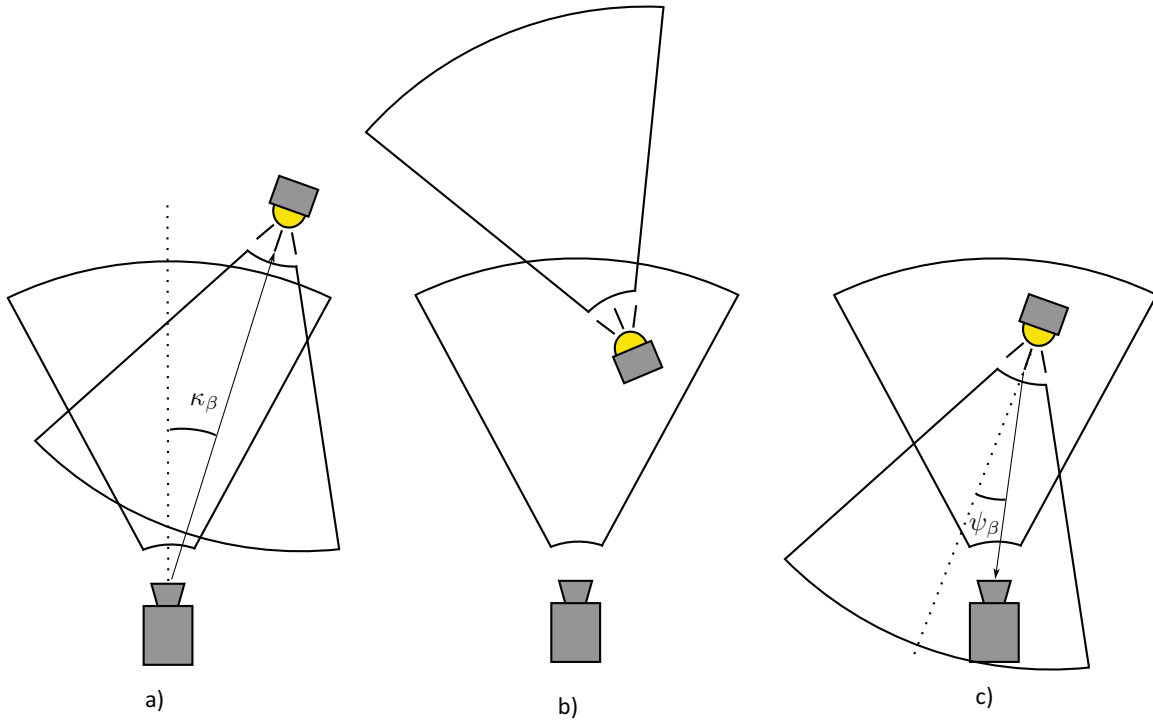| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 23: Three cases of relative pose between the camera and the light source where the camera cannot see the light source in a) and b) and where the camera can sense the light source in c).
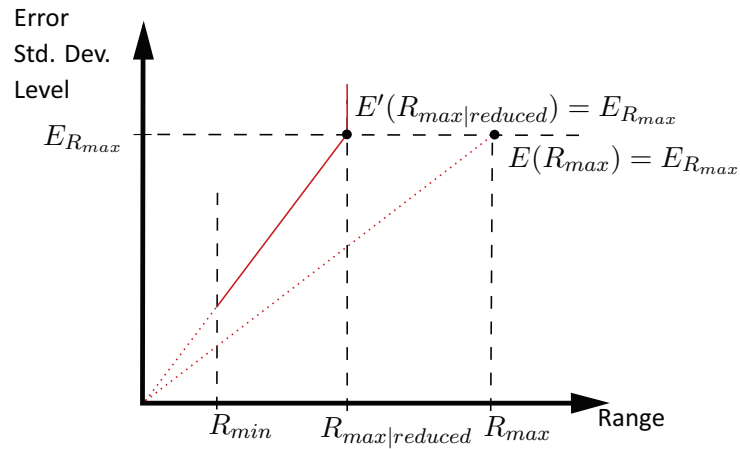

Figure 24: The optical positioning system error model. The error is defined as a function of range and relative orientation.

because of turbidity Q and whether or not the light and camera are in each other's fields, according to:

$$
R_{max|reduced} = \begin{cases} R_{min} & if \quad 2\kappa_\alpha \geq K_\alpha \\ R_{min} & if \quad 2\kappa_\beta \geq K_\beta \\ R_{min} & if \quad 2\psi_\alpha \geq \Psi_\alpha \\ R_{min} & if \quad 2\psi_\beta \geq \Psi_\beta \\ R_{max}(1-Q) + R_{min}Q & else \end{cases} \tag{32}
$$

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where κ_β and κ_α are the relative bearing and azimuth angle of the light relative to the camera's frame, respectively, and ψ_β and ψ_α are the relative bearing and azimuth angle of the camera relative to the light's frame, respectively, as shown in Figures 23 a) and c).

3.5.7   Additional sensors

The inertial navigation system is present on each marine vehicle and measures or computes from measurements the position, orientation, and velocity of the vehicle. The output of the INS block is used by various controllers throughout the overall system. The INS is currently modelled as an ideal sensor and thus the output signals are the true position, orientation and velocities of the vehicles.

The docking mechanism is also given joint displacement sensors. This is required so the MDC knows the pose of the dock, and therefore the 3D location and pose of the dock mounted sensors. These sensors are also assumed to be ideal until modelling their error becomes important.

3.6   Signal modifiers

3.6.1   Overview

A signal modifier is a control system block that has at least one input and at least one output. It takes one or more signals for input, alters them in some fashion and outputs the modified signal to the intended signal destination. There are currently three types of signal modifiers that were implemented in the simulation software. A sensor fusion block, discussed in Section 3.6.2, and a signal limiter, discussed in Section 3.6.3, and a low pass filter, discussed in Section 3.6.4.

3.6.2   Sensor fusion

The UUV and submarine each have two PSSs which provide them with relative position information of the other vehicle. Each sensor has a different level of accuracy of their measurement depending on operating conditions. In order to manage the varying degrees of accuracy between the sensors and improve the measurement, a simple sensor fusion block is used.

Currently, the sensor fusion block detects the amount of noise present in the signals of each sensor connected to it and takes a weighted average from them for the output. For each sensor signal flowing into the sensor fusion block, a confidence factor c_j is assigned based on the magnitude of the noise standard deviation (σ_j) as described by Equation 33, where j is the jth sensor connected to the sensor fusion block. The sensor with the lowest error level will have the highest confidence factor, or weighting assigned to it. That sensor will have the most influence on the averaged output of the fusion block.

The confidence factor c_j is calculated by taking the inverse of the specific sensor's σ_j and dividing it by the sum of all the sensors' inverse σ_j. The sum of all the confidence factors will add up to 1.

$$c_j = \frac{\frac{1}{\sigma_j}}{\sum_{k=1}^{N_i} \frac{1}{\sigma_k}} \tag{33}$$

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The output signal value of the fusion sensor, s_{avg}, is computed as a weighted average as:

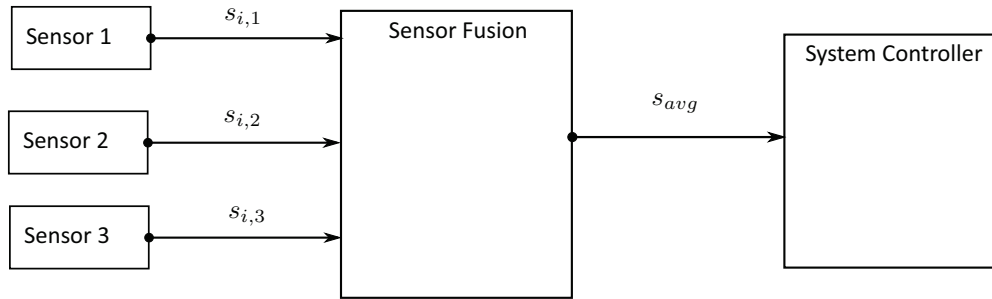$$s_{avg} = \frac{\sum\limits_{j=1}^{N_i} s_{i,j} c_j}{N_i} \tag{34}$$

Figure 25: Sensor fusion diagram.

There exist more advanced sensor fusion techniques such as Kalman filtering which could be employed to replace this simple sensor fusion block implementation. The use of more advanced techniques will be investigated in the future.

3.6.3   Signal limiter

A signal limiter is a signal modifier that is placed in the flow path of a signal to ensure that it doesn't exceed some minimum or maximum. A signal limiter has two parameters, the minimum allowable signal level, s_{min}, and the maximum allowable signal level, s_{max}. Given some input signal, s_i, the output signal, s_o will be modified according to:

$$s_o = \begin{cases} s_{min} & if \ s_i < s_{min} \\ s_i & if \ s_{min} \leq s_i \leq s_{max} \\ s_{max} & else \end{cases} \tag{35}$$

A signal limiter like this is used in this work for cascade PID control of vehicle depth by controlling pitch. The top level controller needs to have its output limited to prevent undesired pitch setpoints from being supplied to the pitch controller. This can be seen in Sections 3.10 and 3.11.

3.6.4   Signal low pass filter

A signal low pass filter is a signal modifier that is also placed in the flow path of a signal. The input parameter is the desired cut off frequency, f_c, of the filter. The output signal attenuates the frequencies above the chosen cut off frequency. A filter time constant, RC, is established based on the cut off frequency.

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$$RC = \frac{1}{2\pi f_c} \tag{36}$$

The smoothing factor, ϵ, is then calculated based on the time constant and the sampling period, τ_s.

$$\epsilon = \frac{\tau_s}{RC + \tau_s} \tag{37}$$

The output signal as a function of time, $s_o(t)$, is then constructed using the smoothing factor and the previous output value.

$$s_o(t) = \epsilon s_i(t) + (1 - \epsilon) s_o(t - \tau_s) \tag{38}$$

3.7 Docking mechanism controller

The docking mechanism is a 2 DOF planar manipulator consisting of a revolute joint followed by a prismatic joint. A simplified diagram of the mechanism can be found in Figure 26. A description of the joint naming convention used here is provided in Part 2 of this report. The dynamics of the articulated body is also discussed in Part 2 of this report. The joint frames $\mathbf{J}_1$ and $\mathbf{J}_2$ are shown oriented as modelled in the simulation software. Both links are rigid bodies whose rigid body frames are located at $\mathbf{CG}_1$ and $\mathbf{CG}_2$. The optical PSS's camera and short range EM positioning system's sensor is mounted to the first link coincident with the $\mathbf{J_2}$ frame for simplicity. The position of the two PSS's sensors is located at a position $\mathbf{s}$ from the mechanism's base frame.

The docking mechanism controller determines what the desired joint displacements. These desired joint displacements are provided to the docking mechanism joint actuators. The wing fairing's pitch DOF is controlled using a second order transient response model. The commanded wing fairing pitch is achieved kinematically according to it transient response model. The prismatic joint's actuator uses a PID controller for achieving its desired displacement. It takes in the desired joint displacement, compares it against the actual joint displacement, and computes the force required to actuate the mechanism and achieve the desired displacement. This section describes how the desired joint deflections are determined in order to pass these onto the joint actuators.

The PSS signals, the relative Cartesian position of the UUV, is expressed relative to the sensors' reference frame, $\mathbf{S}$. The joint displacements θ_1 and d_2 are known from the joint displacement sensors. This controller determines by how much the joints must be deflected to match the UUV's position in the transverse plane: θ_1^* and d_2^*. The relative position of the UUV as perceived by the sensors, $\mathbf{p} = [x_p, y_p, z_p]^T$, is used to determine how the manipulator's joints must be deflected according to:

$$\delta\theta_1 = \arctan\left(\frac{-z_p}{x_p}\right) \tag{39}$$

$$\theta_1^* = \arctan\left(\frac{|\mathbf{s}|\sin(\theta_1) + |\mathbf{p}|\sin(\delta\theta_1)}{|\mathbf{s}|\cos(\theta_1) + |\mathbf{p}|\cos(\delta\theta_1)}\right) \tag{40}$$

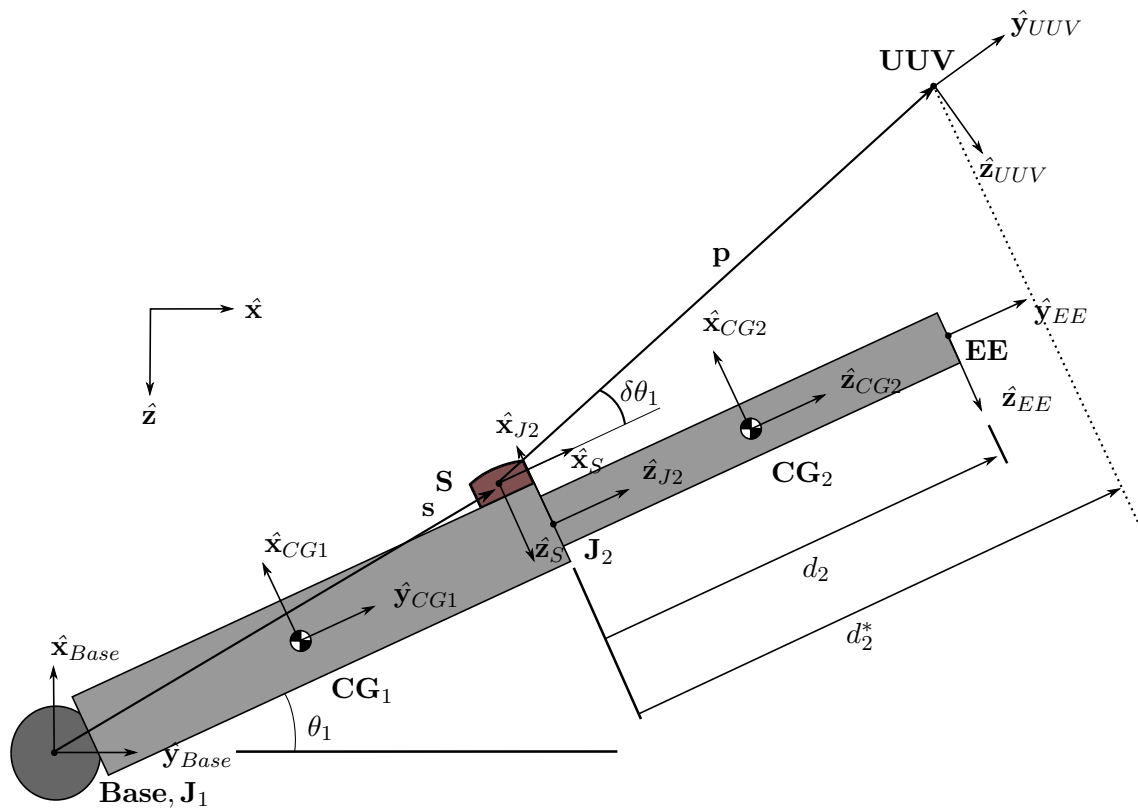$$d_2^* = |\mathbf{p}|cos(\delta\theta_1) \tag{41}$$

Figure 26: A 2 DOF representation of the docking mechanism showing the various reference frames.

Determining the desired deflections of the manipulator joints was simplified by the fact that the sensors' frames are both coincident and have the same orientation as the global frame. Note that, for future work, the frame location difference between $\mathbf{J_2}$ and the individual sensor frames may need to be specified.

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3.8 UUV's Docking Controller (UDC)

Figure 27 shows in greater detail but at a high level the UUV's autopilot control system and how it interacts with the UUV Docking Controller (UDC). It shows the UDC providing instructions to the autopilot's guidance control system.

The relative position information obtained from the PSSs are passed to the UDC. The PSSs consist of the acoustic and the intermediate range EM PSS with sensor fusion between them.

During stage 1 of the docking procedure, the UDC will tell the autopilot's Guidance system to use Homing mode and will pass it the target bearing and range information. The Guidance system then makes appropriate decisions to home in on the target. All other homing strategy parameters were provided by the submarine at the start of stage 1.

When the UUV enters the docking envelope, the MDC, which is found on the submarine and discussed in Section 3.9, triggers the UDC to enter stage 2. During stage 2, the UDC instructs the UUV's autopilot to use Steady Flight mode and provides it with the desired state it must maintain.
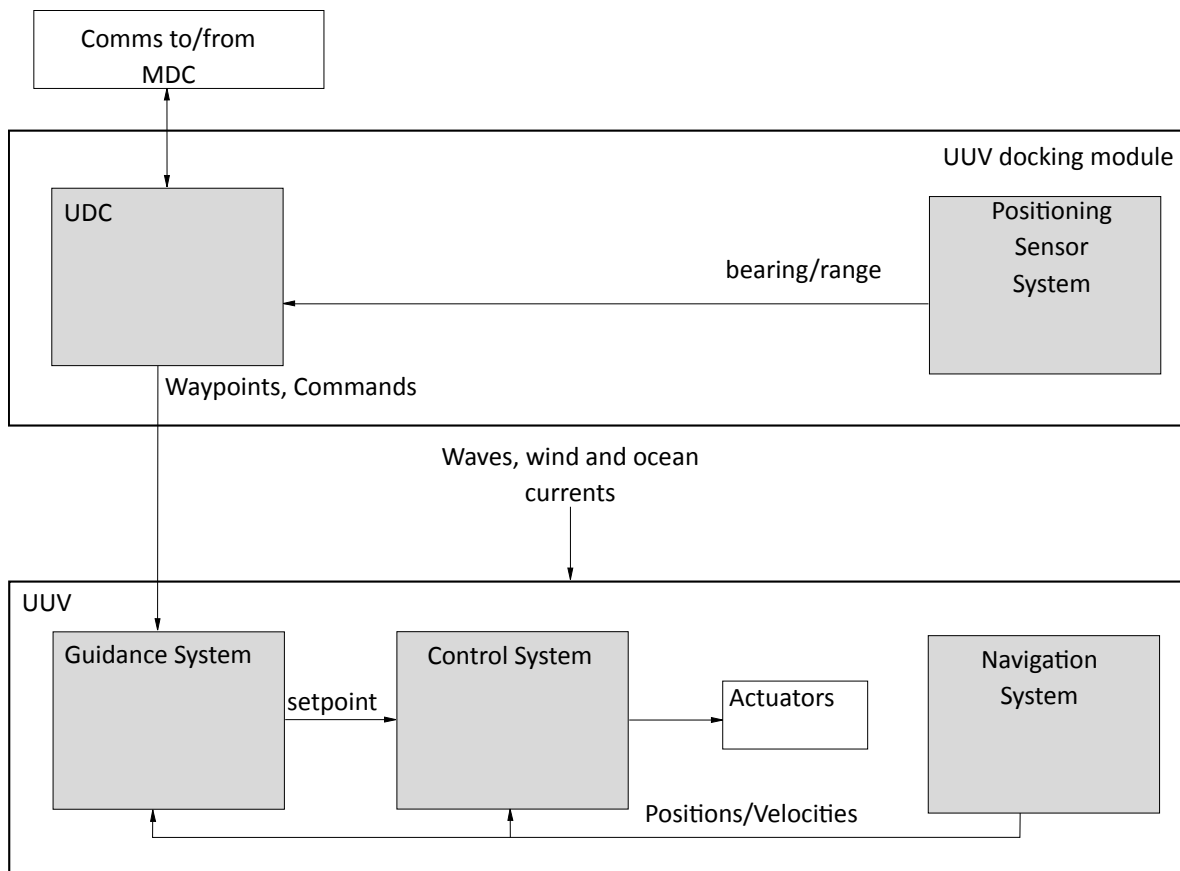

Figure 27: Simplified signal flow diagram of the UUV autopilot system and its interaction with the docking control system. This figure is an adaptation of a Figure found in [4].

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3.9   Submarine's Master Docking Control system (MDC)

A higher detail signal flow diagram of the submarine's control system is shown in Figure 28. It is very similar to the UUV's control system except that the submarine also has a docking mechanism controller. The Master Docking Control system (MDC) is in charge of orchestrating Stage 2 of the docking procedure including sending periodic course corrections to the UDC. It obtains relative position/orientation information as input signals from its PSSs. Its PSSs consist of the short range EM PSS as well as an optical PSS with sensor fusion between them. From this information the MDC then instructs the Dock Mechanism Controller where to move its end effector (capture mechanism) in order to match the UUV's position and capture it.

During the course of the docking simulation, the submarine will remain in Steady Flight mode, thus the docking controller will not need to interact with the Guidance control block. The MDC will mostly be in charge of passing information to the docking mechanism controller over the various phases of the docking procedure. It can, however, send commands to the UDC to modify its Steady Flight mode setpoints and ensure it remains inside the docking envelope. It also provides feedback to the submarine pilot and crew about the state of the docking procedure.

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Figure 28: Simplified signal flow diagram of the submarine autopilot system and its interaction with the docking control system as well as the active dock arm's control system. This figure is an adaptation of a Figure found in [4].

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3.10   Review of the UUV's control systems

A detailed signal flow chart of the UUV's control systems is shown in Figure 29.

The MIMO PID controller controls heading and speed using the rudder plane and thruster respectively, and controls depth by commanding pitch modifications which are sent to a pitch controller. The autopilot has pitch limits to prevent the UUV from achieving undesirable states which is handled by first passing the pitch setpoint signal through a signal limiter first. The pitch controller then actuates the stern planes to achieve the desired depth setpoints.

In order to home in on the submarine, during Stage 1, the UUV will use the PSSs to determine the relative bearing and range of the submarine relative to the UUV. The PSSs feed their signals to the UDC which, which depending on the stage of the docking procedure, will instruct the guidance system on what to do. The guidance system makes high level decisions about where to go by target tracking via constant bearing homing or maintaining steady flight.

The UDC is capable of communicating with the submarine's MDC by some means such as an acoustic or EM modem (green block). An example communication could be receiving a command to transition from stage 1 of the docking procedure to stage 2. Another could be receiving course correction commands during stage 2. Communication error models are not considered.

The motion control system's output contains the commanded appendage states which the appendage models will attain using a 2nd order transient response model similar to the docking mechanism's wing fairing. The design of the motion control systems will evolve to meet the needs of the simulation.

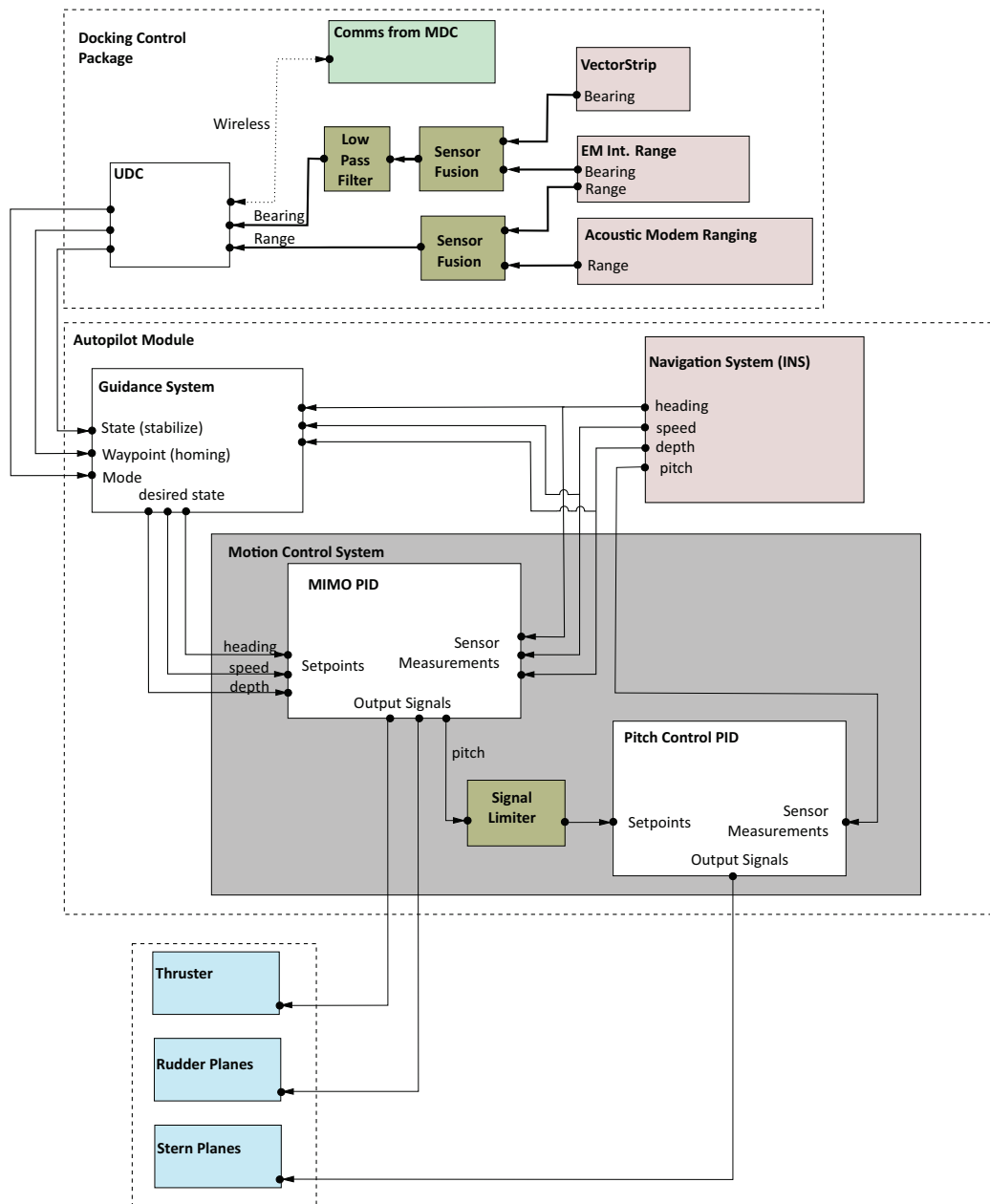| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 29: Detailed UUV control system flow diagram.

3.11 Review of the submarine's control system

A detailed signal flow chart of the submarine's control systems is shown in Figure 30. Its autopilot is currently set up identically to the UUV's, with the exception of control system settings. The control systems will evolve to control the bow planes and employ more complicated control methods.

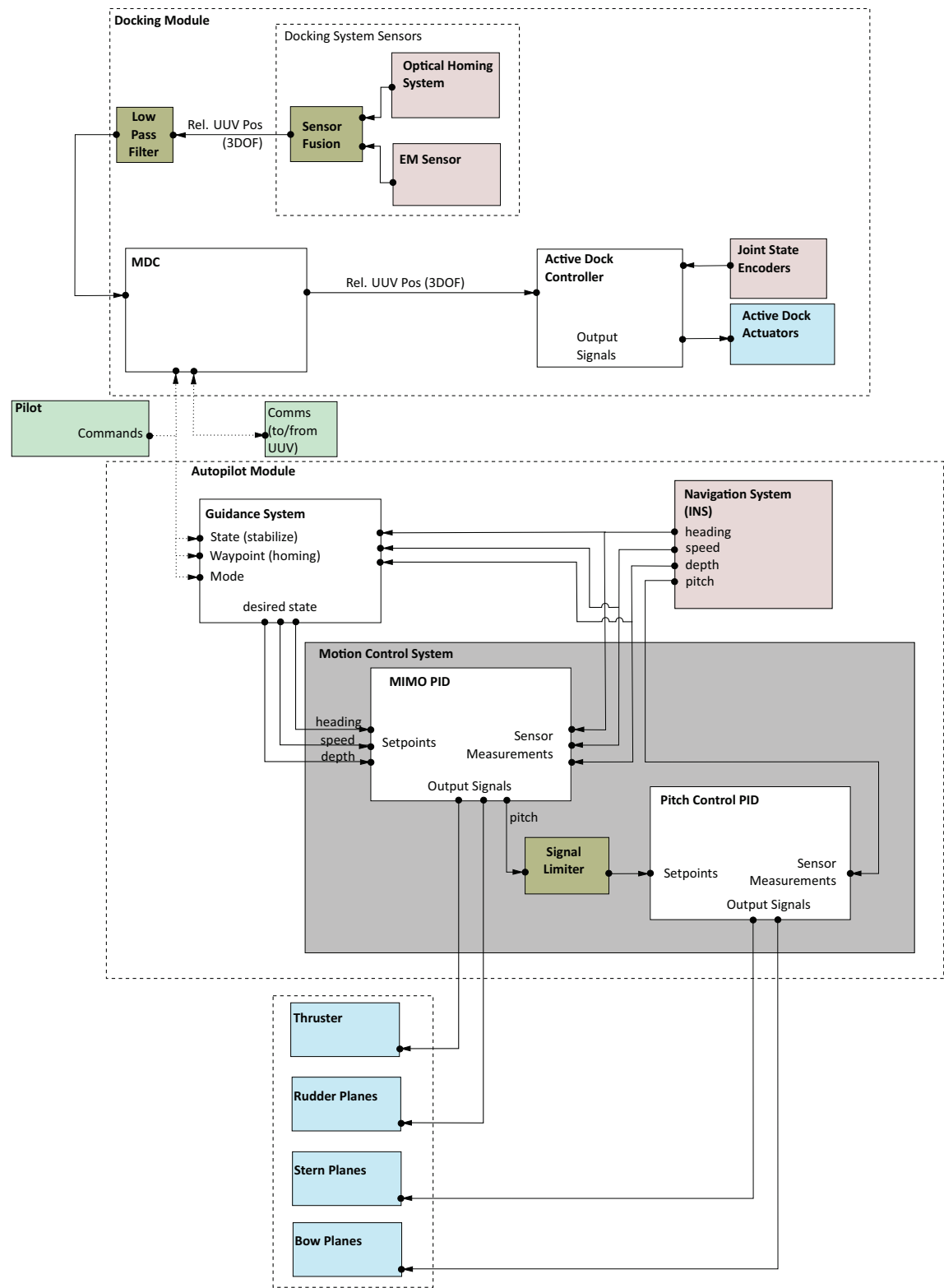| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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The submarine's MDC provides tracking information to the Active Dock Controller. The docking mechanism controller takes in from the MDC the position of the UUV relative to the PSSs. It also takes in joint encoders signal to determine joint actuation actions required to achieve the desired end-effector location.

During phase 2 of the docking procedure, the submarine's docking control system can send commands to the UUV to hold certain headings, depths, and speeds and may send correction commands as needed to ensure the UUV remains in the docking envelope and passes through the actuation plane. The docking system controller uses PSSs to determine the position of the UUV. From this, the desired manipulator end effector position is determined. With the docking arm's docking target (end effector) tracking the UUV, capture can be achieved.

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Figure 30: Detailed submarine and dock control system flow diagram.

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4 Verification

4.1 Overview

Various simulation scenarios were run to demonstrate the functioning of the various components of the UUV docking simulation. For the verification scenarios found in Sections 4.3 through 4.6, two marine vehicles were used, one with a source and one with a sensor. For these scenarios, the sensor remains stationary as the source travels across the sensor's field of detection. The purpose of these tests is to demonstrate statistical error modelling functionality of the four modelled sensor types: acoustic, EM (intermediate and short range), and optical. The sensor models are subject to change as development continues.

Sections 4.7 and 4.8 offer simulation results for two verification scenarios that demonstrate the use of the control system in both steady state flight and constant bearing homing modes reflectively. Sections 4.9 and 4.10 are demonstration simulations with a focus on the active dock's ability to track the UUV during stage 2 and that ability to control position in harsh environmental conditions respectively.

4.2 Model setup

4.2.1 Overview

This section describes the setup of the 4 PSSs in the various verification tests found in this section.

4.2.2 Acoustic PSSs

The model parameters for the acoustic ranging PSS and acoustic vector PSS are found in Tables 2 and 3 respectively.

Model parameter	Value
SL	120dB
NL	55dB
R_{min}	0m
R_{max}	1000m
k_r	60

Table 2: Acoustic ranging PSS model parameters for Acoustic tracking test.

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Model Parameter	Value
SL	120dB
NL	55dB
R_{min}	0m
R_{max}	1000m
k_r	2
k_b	2
f	2000Hz
V_s	1400m/s
d	0.5m

Table 3: Acoustic vector PSS model parameters for Acoustic tracking test.

4.2.3   EM PSSs

The model parameters for the short range and intermediate range EM PSSs are found in Tables 4 and 5 respectively.

Model parameter	Value
R_{min}	0.1m
R_{max}	10m
k_r	0.01

Table 4: Shortrange EM PSS model parameters for EM tracking test.

Model parameters	Values
R_{min}	50m
R_{max}	3m
k_r	0.01
k_r	0.0001

Table 5: Intermediate range EM PSS model parameters for Sensor fusion test.

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4.2.4   Optical PSS

The model parameters for the optical PSS are found in Table 6.

Model parameters	Values
R_{min}	0.1m
R_{max}	10m
k_r	0.1
K_β	50deg
K_α	50deg
Ψ_β	60deg
Ψ_α	60deg
Q	0.0

Table 6: Optical PSS model parameters for EM tracking test.

4.3   Acoustic tracking test

The purpose of this test is to demonstrate the relative positioning capabilities of both the acoustic vector positioning system as well as the acoustic modem ranging system. This is accomplished by monitoring the error levels in the sensors' output signal as the range between the source and sensor changes with time.

To demonstrate the acoustic positioning system models, the source is initially located 500 m away from the sensor and travels towards the sensor at 10 m/s. The source will not come closer to the sensor than 50 m as shown in Figure 31. The simulation terminates after 200 seconds when the source has traveled 500 m past the sensor. The sensor parameters were set according to the values in Tables 2 and 3.
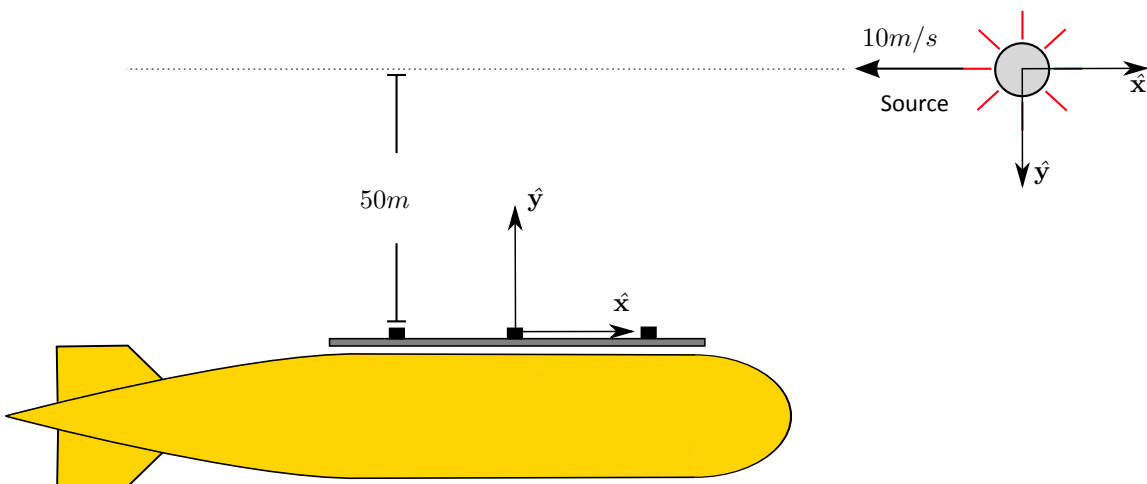

Figure 31: Acoustic positioning system demonstration test setup.

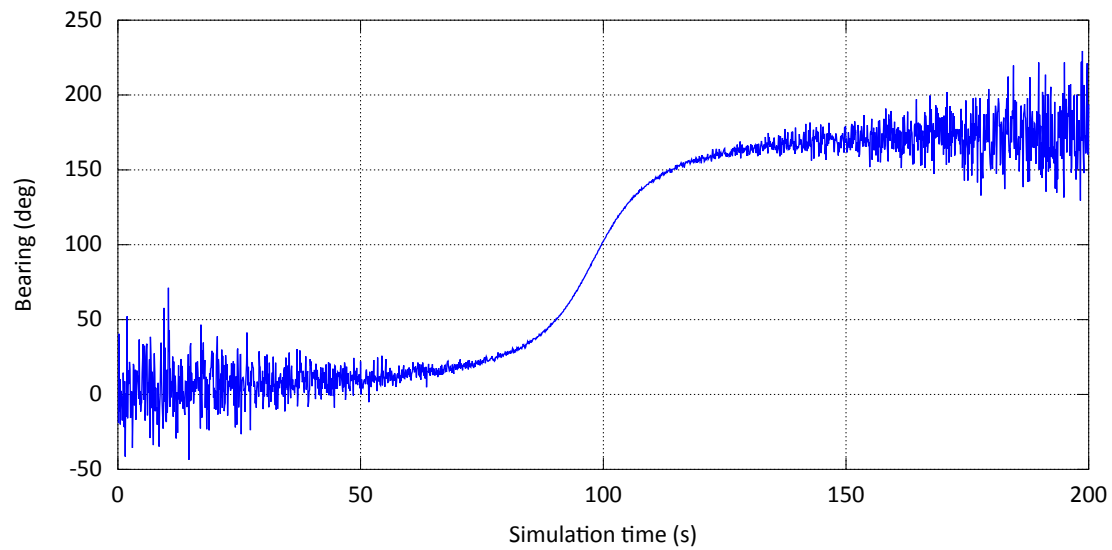| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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4.3.1 Simulation Results

Over the course of the simulation, the distance between the source and the sensors reduces and eventually increases again as the source travels past the sensor. The true distance between the source and sensor is plotted in Figure 32. The bearing measurement and its error standard deviation noise level are plotted in Figures 33 and 34 respectively showing how the bearing measurement noise level is greatest when the distance between the source and sensor is greatest. As the source gets closer to the sensor, the noise level decreases linearly.

The range as measured by the acoustic modem ranging system and its error standard deviation noise level are plotted in Figures 35 and 36 respectively.
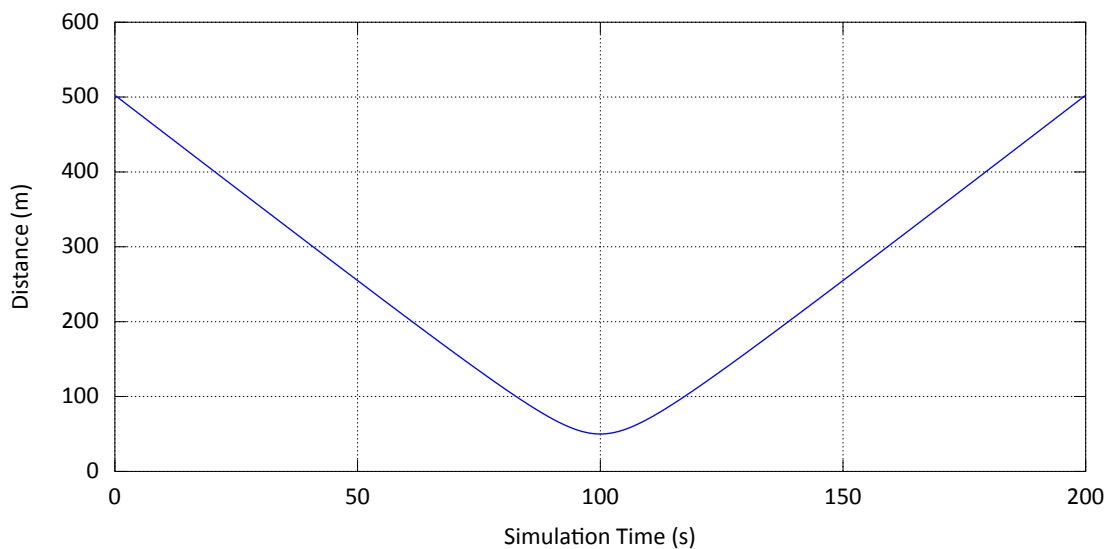
Figure 32: The true distance between the acoustic source and the sensors over the course of the simulation.

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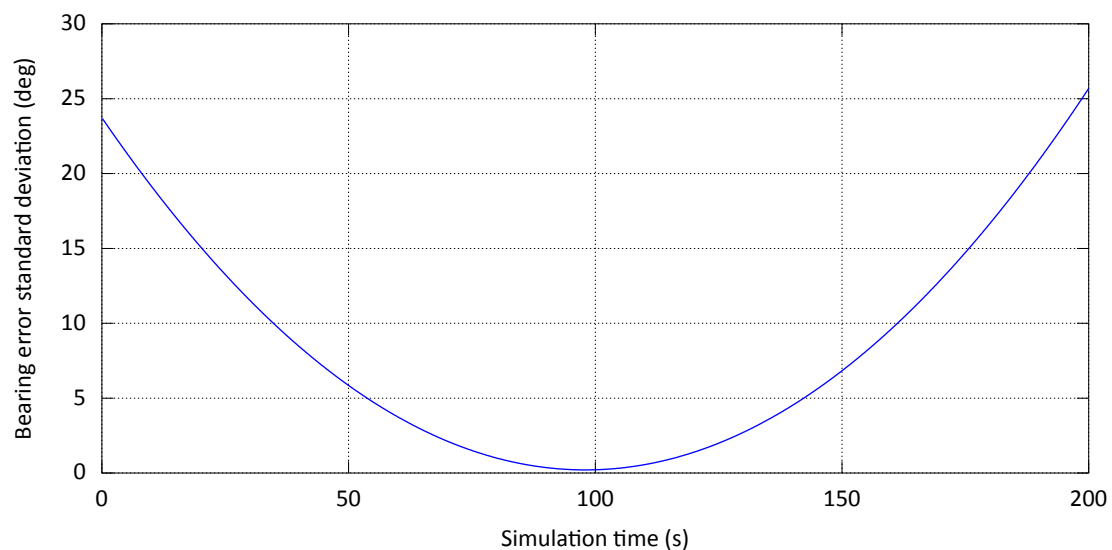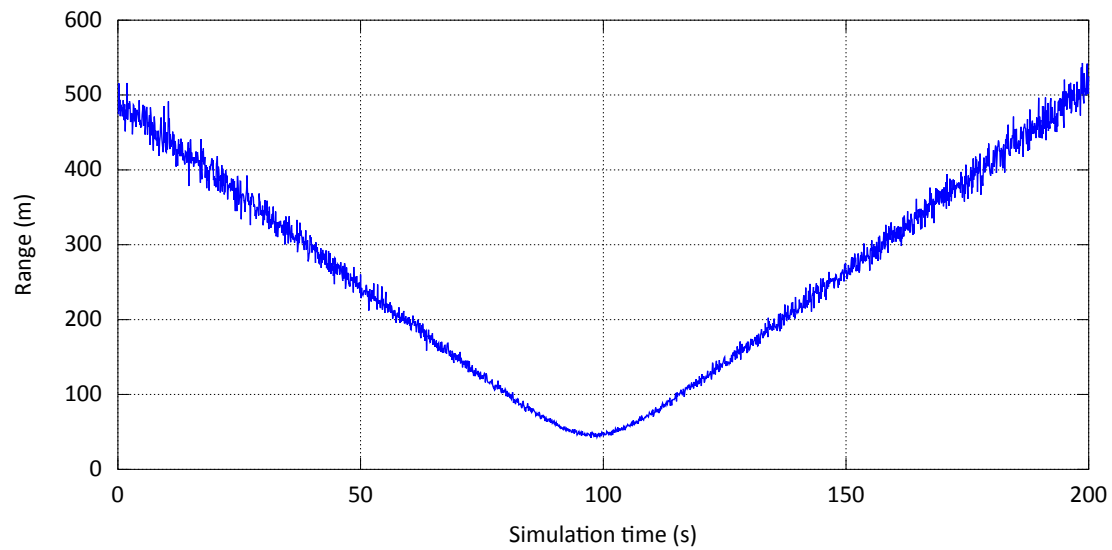**Figure 33: The bearing measurement of the acoustic vector positioning system.**
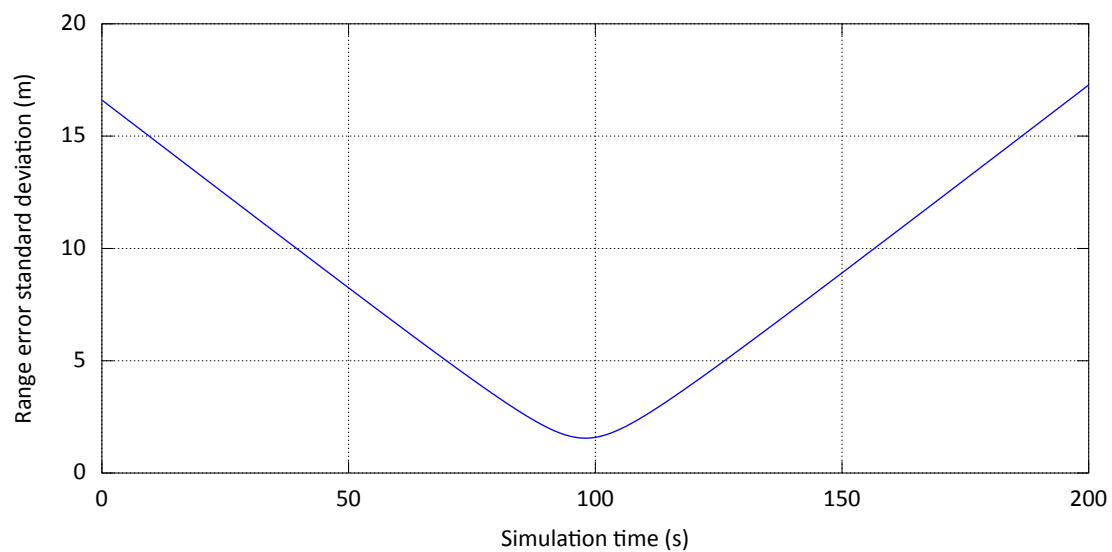

Figure 34: Noise level for the acoustic vector positioning system.

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Figure 35: The range measurement of the acoustic modem ranging system.

Figure 36: Noise level for the acoustic modem ranging system.

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4.4   EM tracking

The purpose of this scenario is to demonstrate the intermediate EM positioning system's capabilities and show how the error levels are affected by the distance between the source and the sensor. The short range EM positioning system provides 3 DOF relative Cartesian position signals while the intermediate range EM positioning system provides bearing and range. They both function very similarly and thus only the short range EM positioning system is shown here.

To demonstrate the EM positioning system, the source is initially located 10m away along the $\hat{x}$ axis and 3m away along the $\hat{y}$ axis from the sensor. It travels toward the sensor along the $\hat{x}$ axis at 0.2m/s as shown in Figure 37. The simulation begins with the source out of the range of the sensor. During this time, the sensor signal should read infinite (1.0e30). It will enter within the sensor range and exit again during which time it will return the Cartesian position of the source with some error. The simulation terminates after 100 seconds.

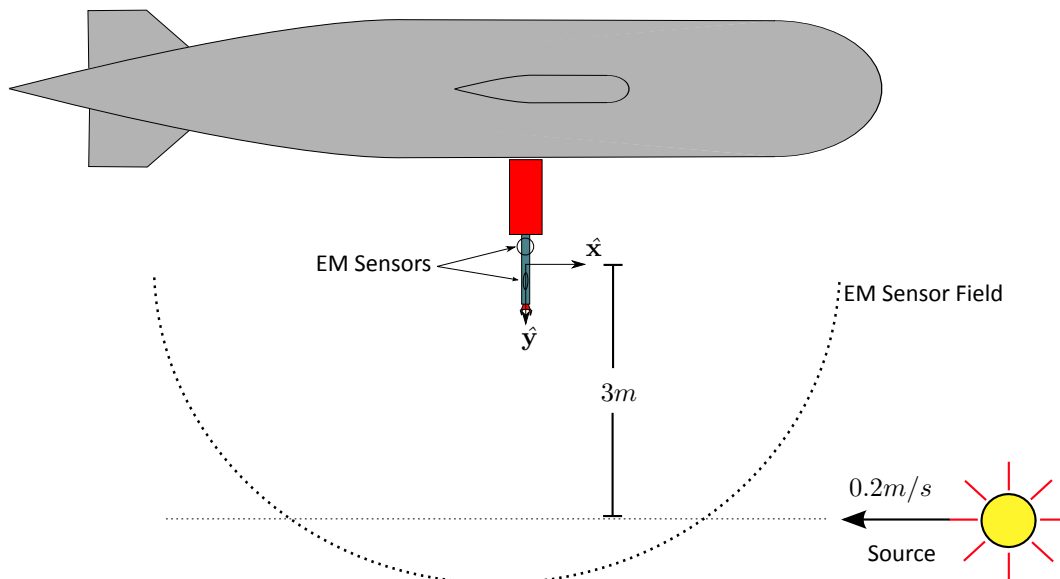The model parameters for the short range EM positioning system used in this scenario are provided in Table 4.

Figure 37: EM positioning system demonstration test setup.

4.4.1   Simulation Results

The magnitude of the noise standard deviation added to the position signal over the course of the simulation is plotted in Figure 38. While the source is out of range of the sensor, the sensor's noise/error level is 1e30 m. To maintain readability of the plot, its y axis is limited to 1 m. Once the source gets within range and the sensor detects it, it registers a range. While the source is in range, the noise standard deviation can be seen decreasing as the source gets closer to the sensor and increases as it travels away.

All three components of the relative position of the source as determined by the sensor is plotted in Figure 39. When the source is outside the range of the sensor, the sensor's signals are 1.0e30, which means it cannot detect the location of the source. However when the source enters the range of the sensor, the sensor outputs the 3 position component signals. The

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signals have noise level that can be seen to reduce in amplitude as the source gets closer to the sensor and increase again when the signal increases.
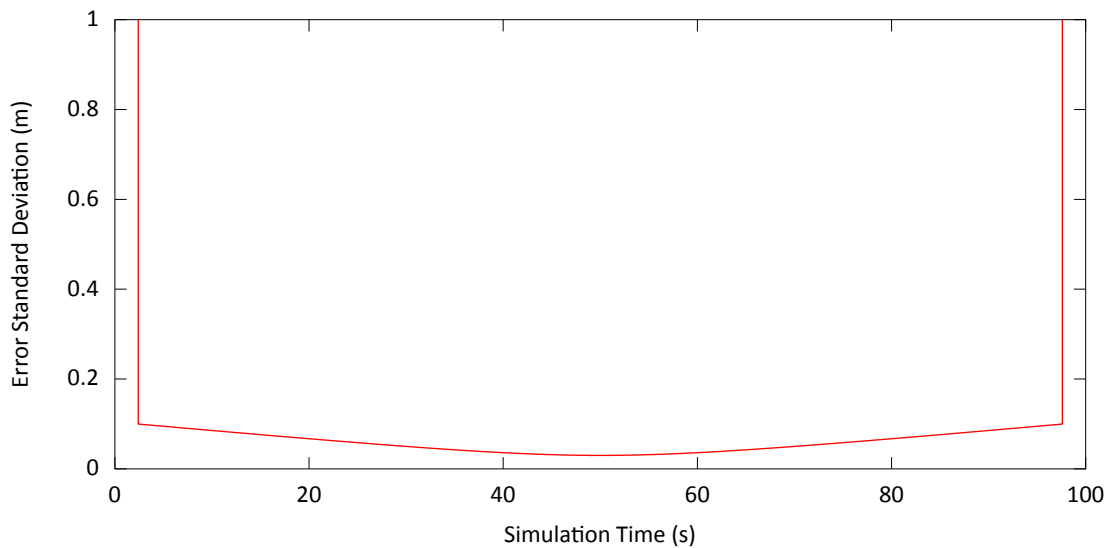
Figure 38: Noise level for the EM positioning system.
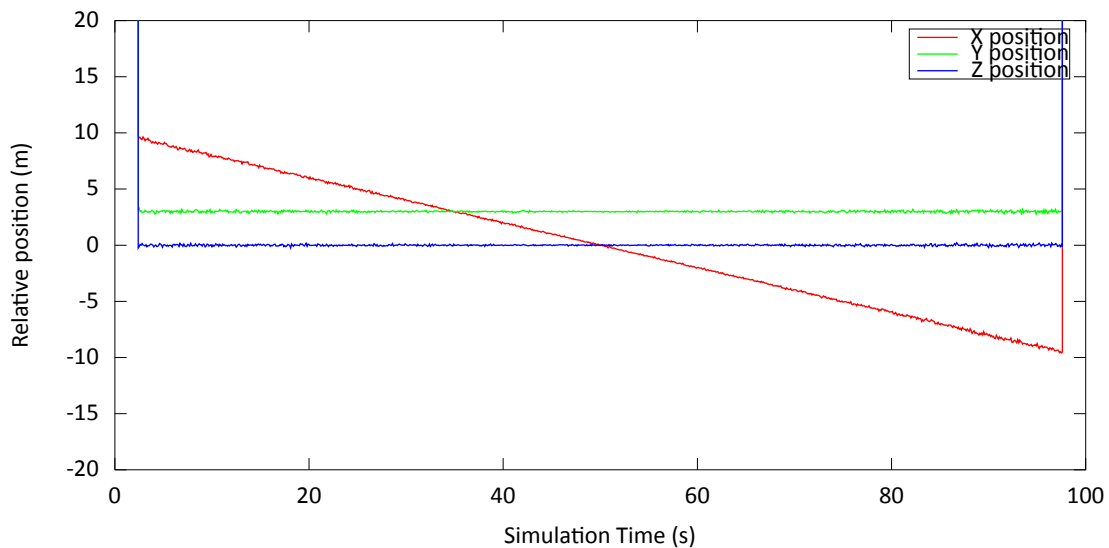
Figure 39: EM positioning system's position output signal

4.5   Optical tracking

The purpose of this scenario is to demonstrate the optical PSS's capabilities and shows how the error levels are affected by the distance and by the relative angles between the source and the sensor.

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To demonstrate the behaviour of the optical PSS, the source is initially positioned 2.5 m away along the $\hat{x}$ axis and -10 m away along the $\hat{y}$ axis from the sensor as shown in Figure 40. The light source is provided an initial velocity of 0.2 m/s along the $\hat{y}$ axis while it rotates about the $\hat{z}$ axis (yaw) at a rate of 45 degrees per second. The simulation terminates after 100 seconds. The model parameters for the optical positioning system were set according to Table 6.

This test will demonstrate the optical sensor's blind spots. Because the range of the light source is varying, there should be a change in the error level as the light source travels through the camera's field of view.
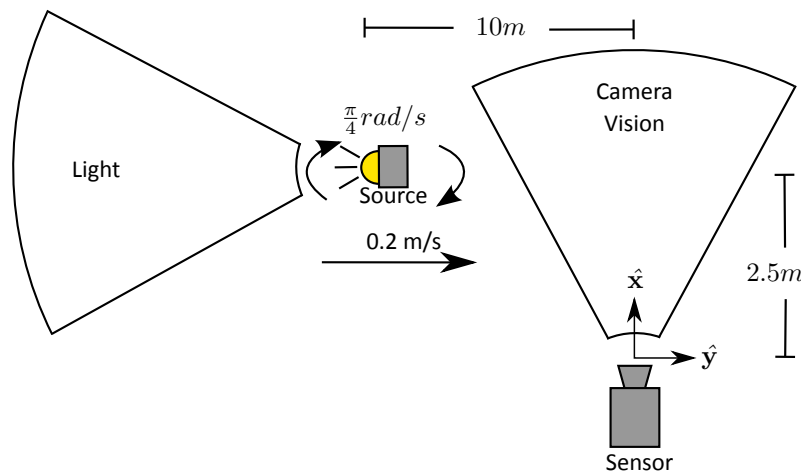

Figure 40: Optical positioning system demonstration test setup.

4.5.1   Simulation Results

The light source spends most of the simulation in the camera's field of vision. However, as the light source rotates, its field of light only overlaps the camera occasionally. The maximum range for detecting the light source is reduced as the light source is not pointing directly at the camera. As can be seen in Figure 41, as the light source travels closer to the camera, the length of time the camera can detect the light source increases since the light source's distance does not break the maximum range limit for as long. This is because the maximum detectable range of the source is reduced when the light and camera are less aligned. Similarly, when the light source is further away from the camera, the light source's error noise level is larger.

When both the camera and the light are overlapping each other's fields, the camera can detect the light source and the computed error standard deviation drops from 1e30 m (undetectable) to a reasonable error value proportional to range. The range of the light source from the camera reduces for half the simulation and increases for the second half which affects the error level when it is detectable. The error level for the signals in Figure 41 can be seen in Figure 42.

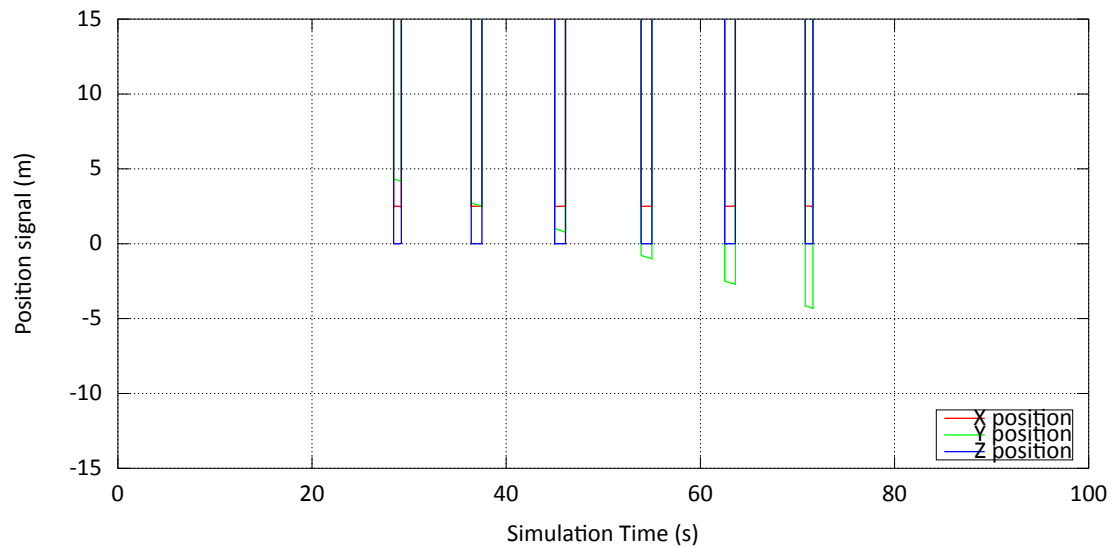| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 41: The 3 DOF position output signals of the optical positioning system.
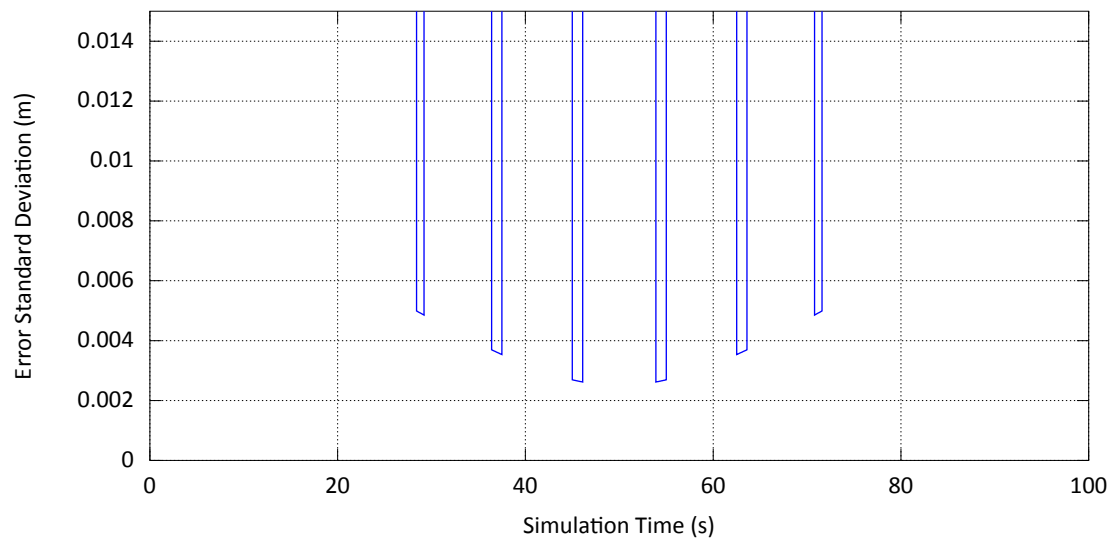
Figure 42: Noise level for the optical positioning system.

4.6   Sensor fusion

The purpose of this test is to demonstrate the functionality of the sensor fusion block. To accomplish this, an intermediate range EM positioning system, which outputs both bearing and range sensor signals, is fused with an acoustic vector positioning system and an acoustic modem ranging system which provide bearing and range sensor signals respectively. The sources are attached to a stationary marine vehicle, while the sensors are attached to a moving marine vehicle as shown

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in Figure 43. The sensor vehicle is initially located 200m away along the $\hat{x}$ axis and 20 m away along the $\hat{y}$ axis from the stationary sensor. The sensor vehicle travels at 2 m/s along in the negative $\hat{x}$ axis towards the sensor.

The acoustic PSSs' parameters were set according to the values in Tables 2 and 3 while the intermediate EM PSS's parameters were set according to the values in Tables 5.

The output signals from both positioning systems are passed through a sensor fusion block which blends the signals together providing a higher weighting on the more accurate sensor signals. The EM positioning sensor is more accurate than the acoustic sensor. However, it cannot detect the source if the range is greater than 100m. When the EM source is out of range of EM sensor, the acoustic sensors receives a high weighting by the sensor fusion block ensuring its output signals are dominated by the acoustic positioning systems' sensor signals. When the EM source enters the EM positioning system's sensor range, the error from the EM positioning sensor will be much smaller than that of the acoustic positioning sensor and thus a higher weighting will be places on the EM positioning sensor's output signals by the fusion sensor block.
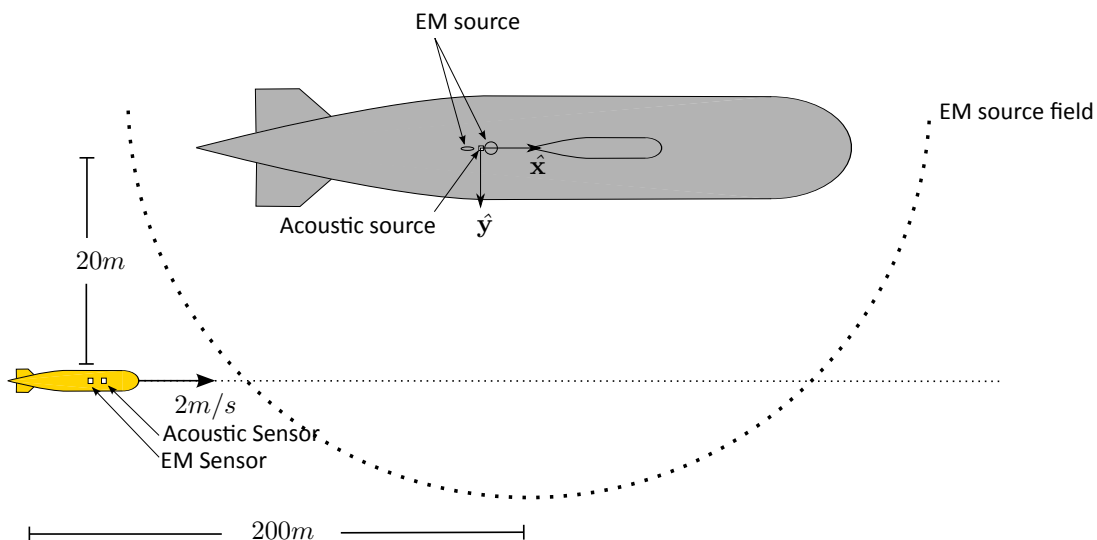

Figure 43: Sensor fusion demonstration test setup.

4.6.1 Simulation Results

The distance between the positioning systems' sources and sensors reduce over time from 200 m to near around 20 m and increase again as the sensor vehicle move past the source vehicle as shown in Figure 44. When the sensor vehicle is within a range of 50m at a simulation time of about 80 seconds, the EM sensor can detect the EM source and the error noise level is greatly reduced. Similarly for the bearing signal, at around 80 second, a noticeable reduction in the signal's noise level is observed in Figure 45. This is due to the sensor fusion block managing the error levels between the attached sensors.
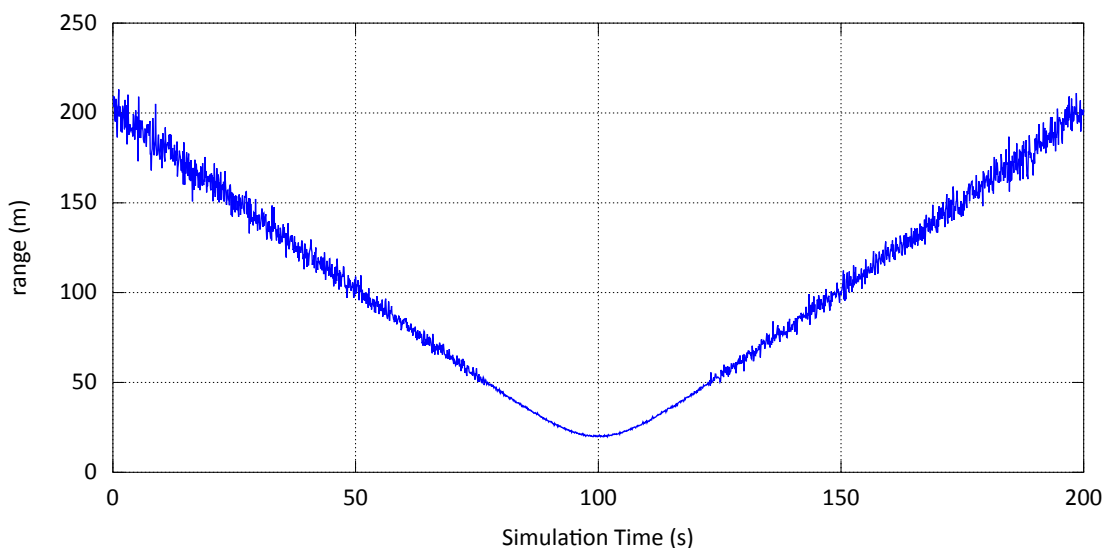
Figure 44: Sensor fusion output range signal as a function of time.
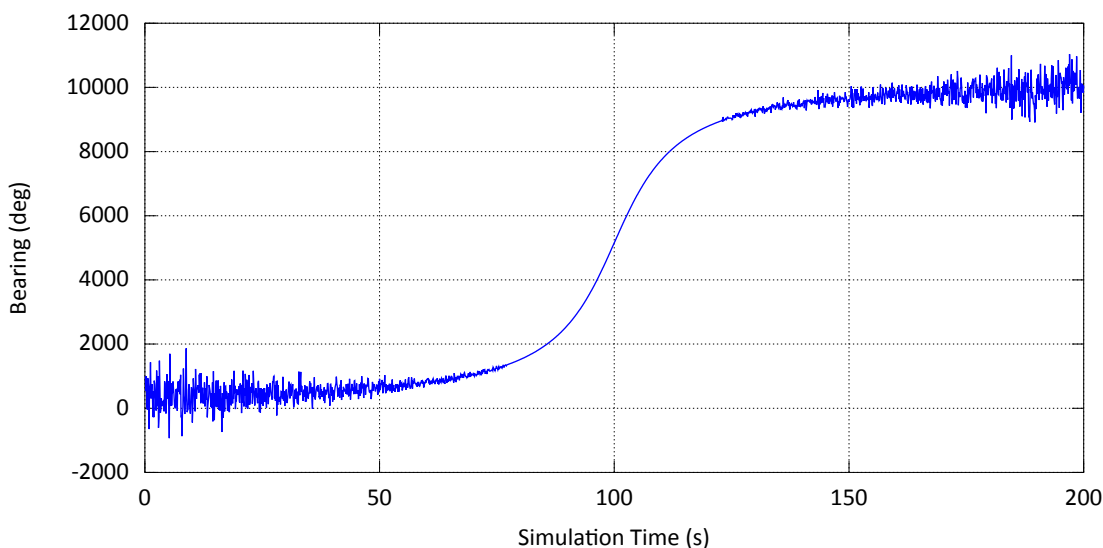

Figure 45: Sensor fusion output bearing signal as a function of time.

4.7   UUV steady state mode

The purpose of this test is to demonstrate the steady state mode of the marine vehicle's autopilot. It also tests the autopilot's guidance system ability to command a setpoint and the motion control subsystem's ability to achieve that setpoint. An unmanned underwater vehicle (UUV) was initialized with vertical and horizontal stabiliser control surfaces and one stern thruster. The UUV was initially located directly below the origin of the global reference frame with an initial heading of 0

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degrees and a depth of 55m. The autopilot's guidance subsystem (`NAVComputer`) was placed in steady state flight mode and told to maintain its depth, heading, and maintain a forward speed of 1m/s. After 50s of simulation time, the UUV is commanded to achieve a heading of 180 degrees and rise to a depth of 15m.

4.7.1 Simulation results

The UUV immediately begins to dive and turn to match the desired heading as can be seen in Figure 46. After approximately 500 seconds of simulation time the UUV is at a depth of 50m and has a heading of 180 degrees. The plot of depth vs time can be seen in Figure 47. There is a slight depth overshoot which is a product of the chosen controller gains.
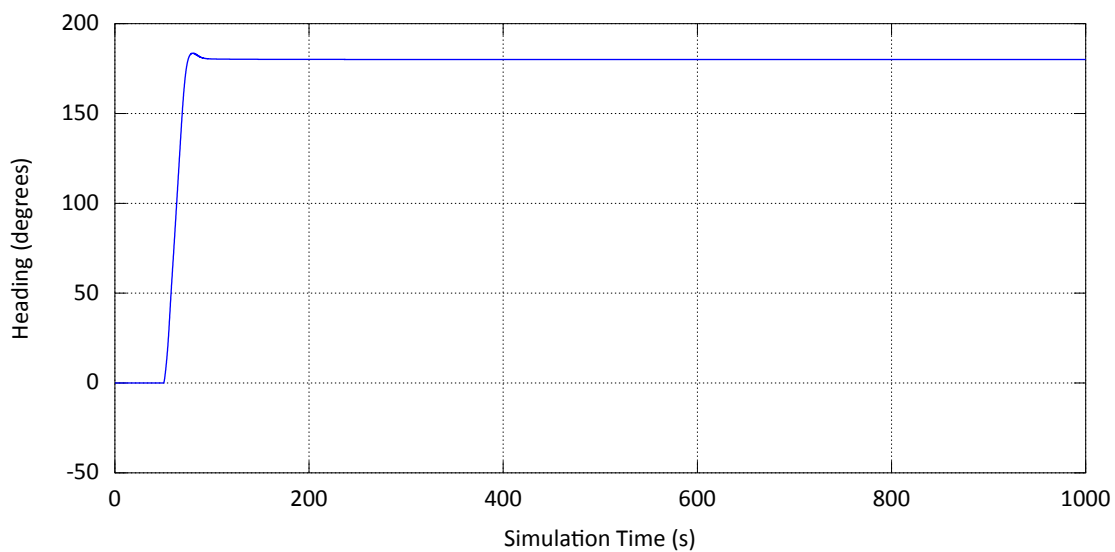

Figure 46: UUV's heading as a function of time.

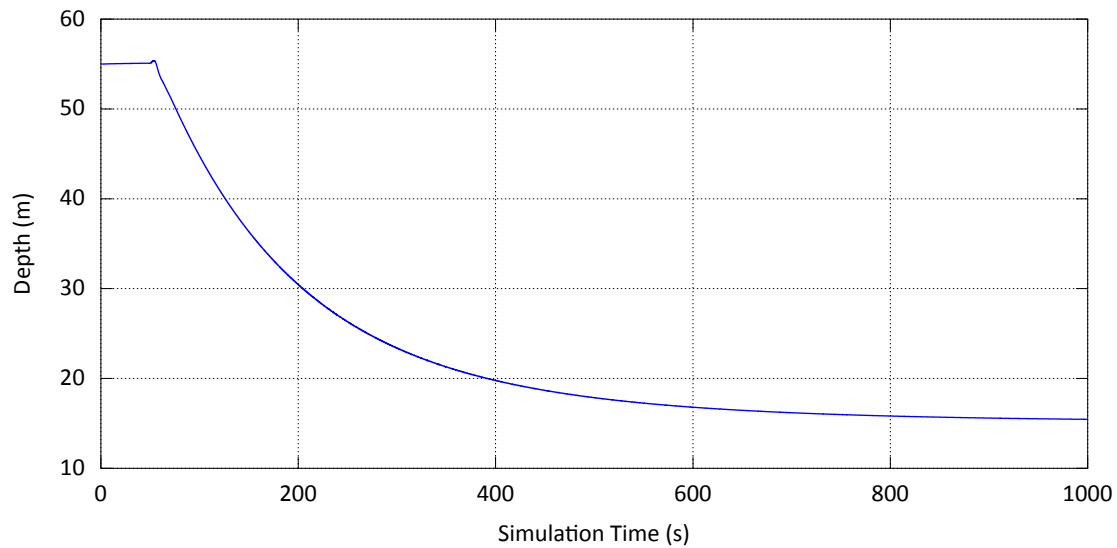| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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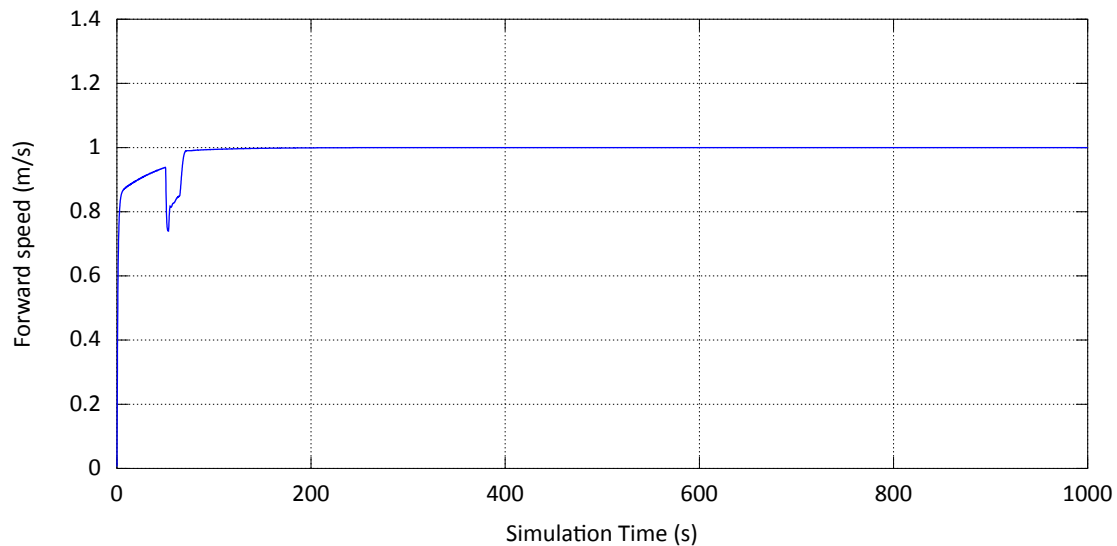**Figure 47: UUV depth as a function of time.**

Figure 48: UUV forward speed as a function of time.

4.8 UUV constant bearing homing mode (Stage 1)

The purpose of this test is to demonstrate the homing capabilities of the docking control system and its ability to complete stage 1 of the docking procedure. This test demonstrates the functionality of the autopilot, docking controller, and sensor systems all working together to achieve the goals of stage 1. This test is carried out in calm water.

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The UUV is provided an acoustic vector positioning system that provides a bearing signal, an acoustic modem ranging positioning system that provides a range signal, and an intermediate range EM positioning system that provides both bearing and range signals. The acoustic positioning systems can provide bearing and range information at much greater distances than the EM positioning system. However, the EM positioning system, within its operational range, provides more accurate measurements. Sensor fusion between the sensors occurs to ensure the most accurate signal dominates between the bearing signal and range signal pairs. The UUV's docking controller uses these fused signals to help the UUV's autopilot guide itself to its target.

The submarine was initially located with a draft of 19m with a forward velocity of 2.37 m/s and a heading of 0 degrees. Attached to the starboard side of the submarine is the docking arm mechanism used to capture the UUV. The UUV has an initial depth of 15m and a forward speed of 1m/s. The docking procedure will occur at a desired depth of 15m. The UUV is initially positioned 650m ahead and 200m to the starboard side of the submarine.

The constant bearing method was setup such that the UUV will attempt to maintain the submarine at a constant bearing of 155 degrees, referenced from the submarine's heading, and will try to keep the source's signals at a bearing of 90 degrees from the UUV's actual heading. This ensures the bearing signal from acoustic vector sensor is most accurate. Based on Equation 1, for a UUV speed of 1m/s, the submarine should be travelling at 2.37m/s. When the distance perpendicular to the submarine's heading of the UUV, y, reaches approximately 30m (y_{UL}), the UUV will begin to taper off its heading such that it enters the docking envelope with the same heading as the submarine, as discussed in Section 3.3.3. When the UUV enters the docking envelope, Stage 1 of the docking procedure ends.

4.8.1 Simulation Results

The simulation began with both the UUV and submarine travelling in the same direction. The submarine is travelling faster than the UUV and is closing the distance between itself and the UUV. A plot of the distance between the submarine and the UUV as measured by the positioning systems is provided in Figure 49.

As this is occurring, the UUV's acoustic vector sensor registers that the bearing of the submarine relative to the submarine's heading reduces to below 155 degrees. This can be seen at a time of ≈ 130 seconds in Figure 50. The UUV then changes its heading in order to close the lateral distance between the two vehicles as can be seen in Figure 51. The UUV then adjusts its speed in order to maintain a constant submarine bearing of 155 degrees relative to the submarine's heading as shown in Figure 52. The bearing α of 155 relative to the submarine's heading corresponds to a bearing γ of 90 degrees relative to the UUV's heading. When the lateral distance y between the two vehicles reaches 30m (y_{UL}) at a time of ≈ 330s, as shown in Figure 51, the UUV starts to taper off its heading in order to ensure it enters the docking envelope with the same heading as the submarine. The UUV's intermediate range EM PSS, which is more accurate than the acoustic vector positioning system, enters functional range at a time of around ≈ 320s and starts providing more accurate bearing signal as shown in Figures 50 and 49. Finally, the UUV enters the docking envelope at a time of ≈ 370s, corrects any differences in heading between itself and the submarine, and drifts towards the docking mechanism which will capture it.

Figure 53 through 56 show screenshots of the visualisation of the simulation. Figure 53 is a screenshot taken at the beginning of the simulation. The UUV and submarine are travelling at the same heading. The UUV has not detected that the bearing of the submarine is less than 155 degrees so it has not yet altered its heading. Figure 61 is a screenshot taken at a simulation time of 130 seconds where the UUV has by now altered its heading to close the lateral distance (y) between itself and the submarine. During this time the UUV is adjusting its velocity to maintain a constant relative bearing to the submarine. Figure 62 is a screenshot taken at a time of 250 seconds, the UUV continues to close the lateral distance between itself and

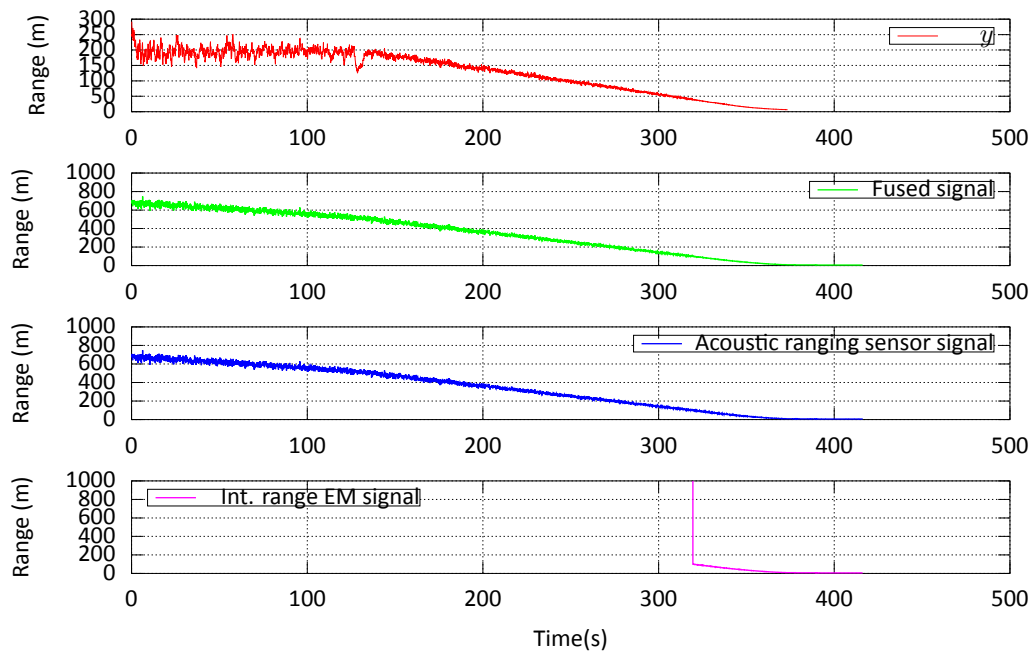| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 49: The range signals from the UUV control system showing relative distance between the two vehicles. Signals shown are as output by the intermediate EM PSS, the acoustic ranging PSS, and the fused signal as well as the lateral distance signal computed by the control system.

the submarine. Finally, the UUV enters the docking envelope at a time of 375 seconds completing stage 1 of the docking procedure.

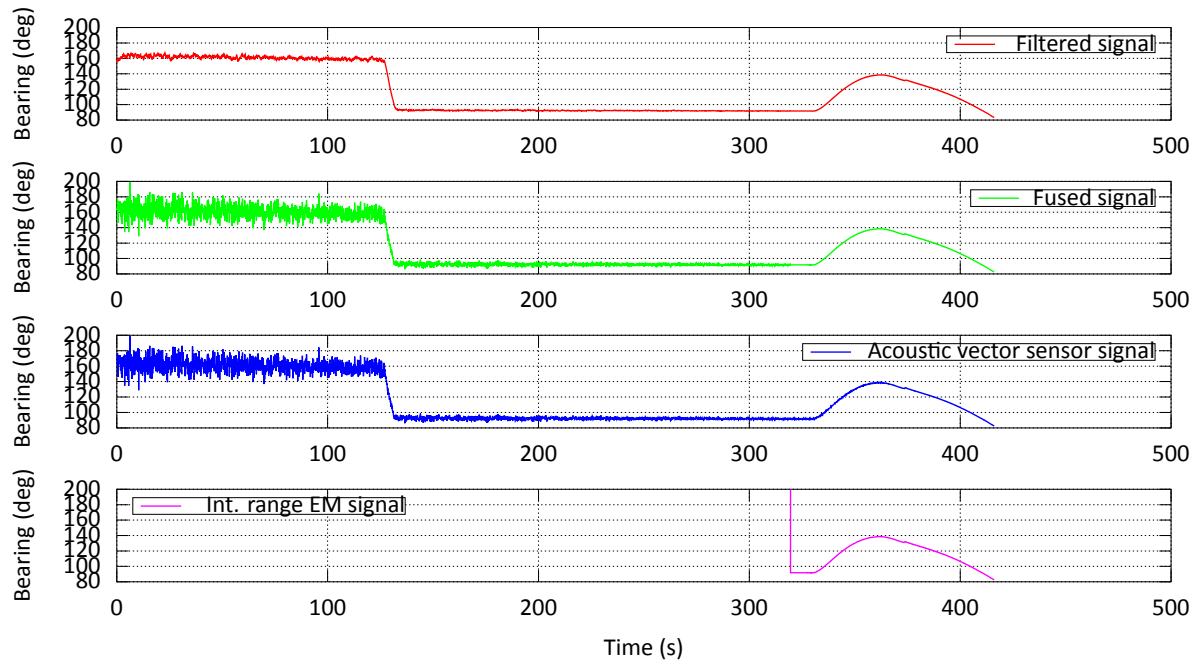| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 50: The bearing signals from the UUV control system showing the bearing of the submarine relative to the UUV's heading. Signals shown are as output by the intermediate EM PSS, the acoustic vector PSS, the fused signal and the filtered fused signal.
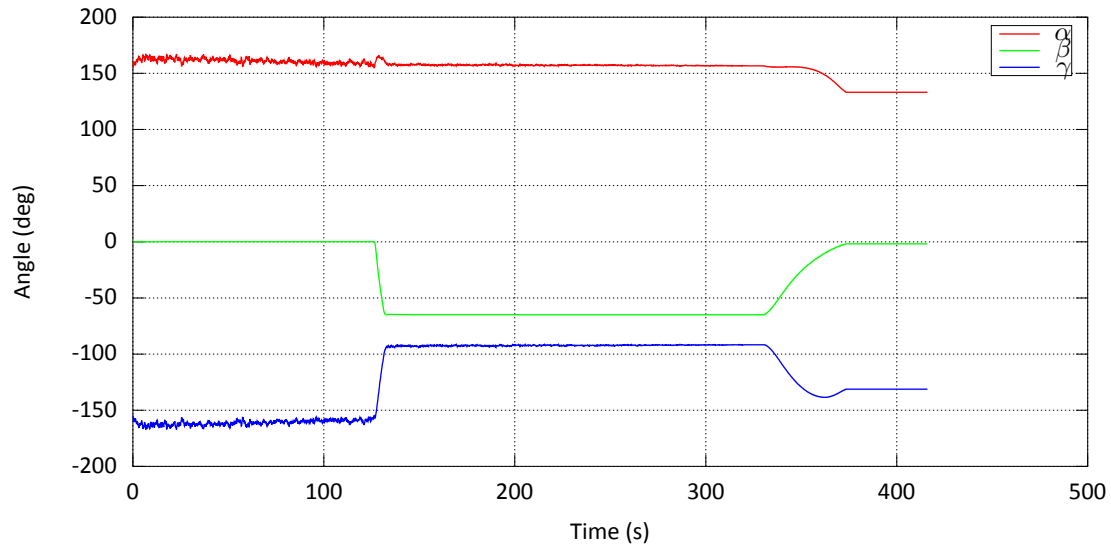

Figure 51: The angles of geometry of the constant bearing homing method as computed by the control system.

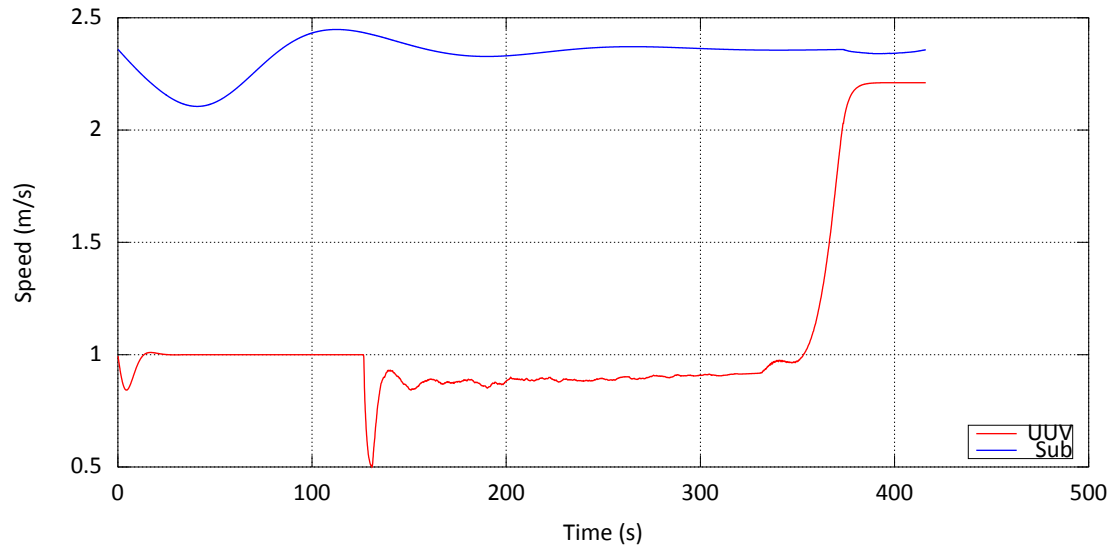| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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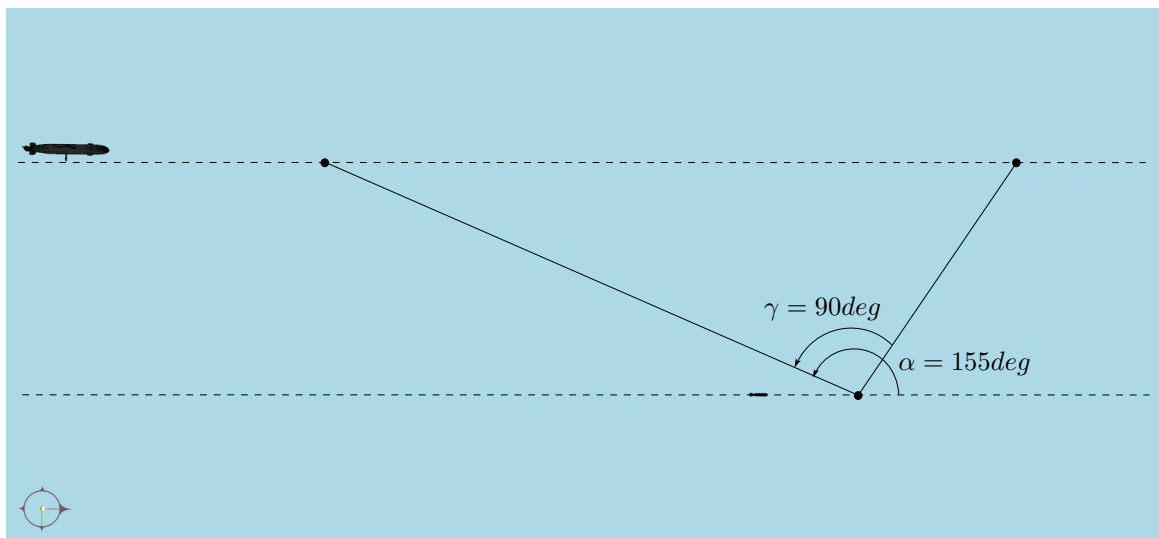**Figure 52: The absolute forward speed of both vehicles.**

Figure 53: A screenshot of the simulation results taken at a time of around 45 seconds. UUV shown scaled 4x larger.

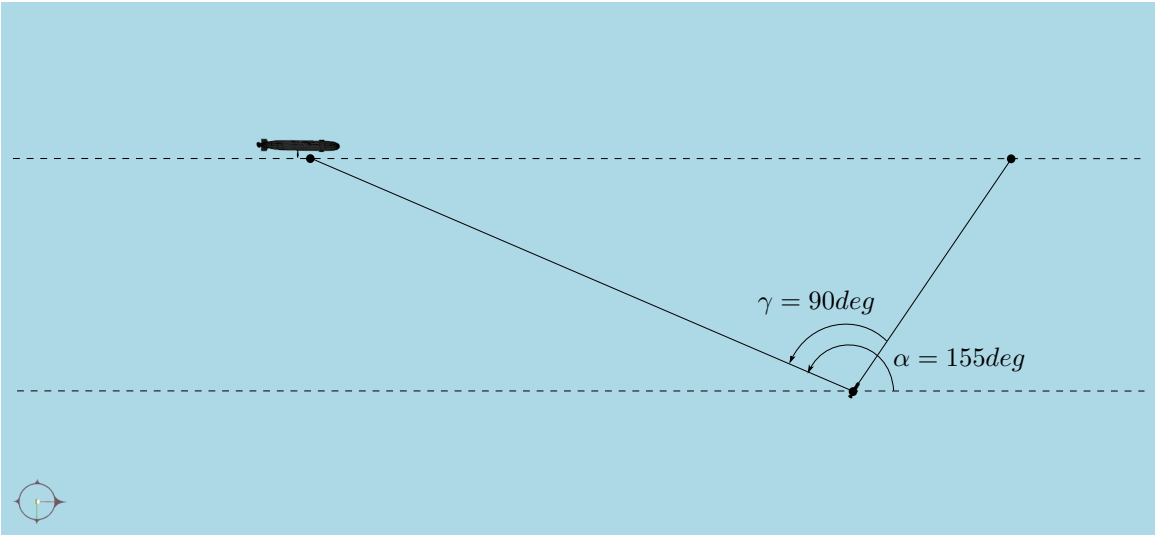| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 54: A screenshot of the simulation results taken at a time of around 130 seconds. UUV shown scaled 4x larger.

Figure 55: A screenshot of the simulation results taken at a time of around 250 seconds. UUV shown scaled 4x larger.

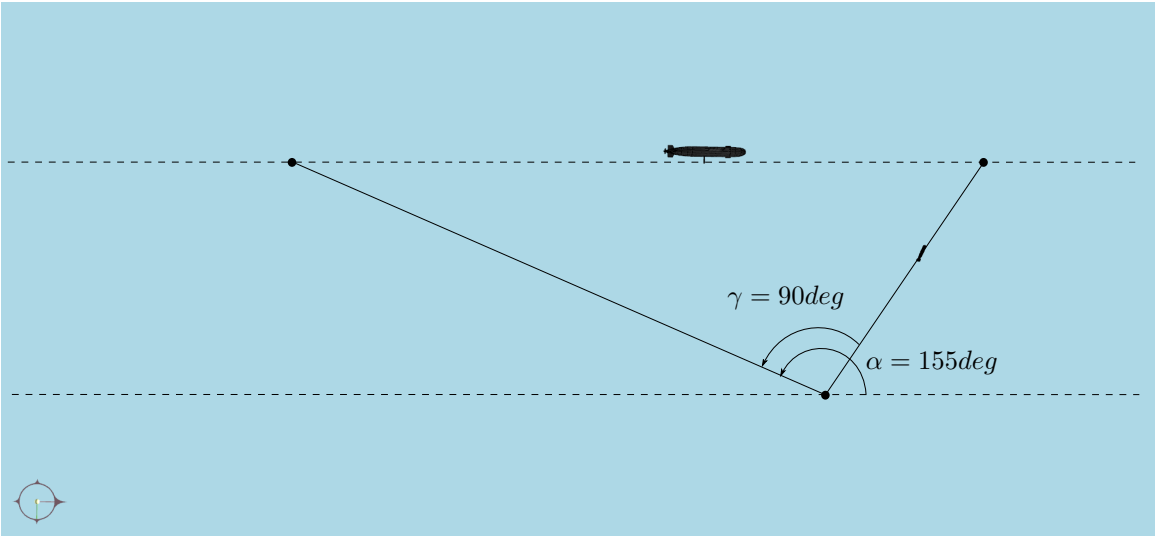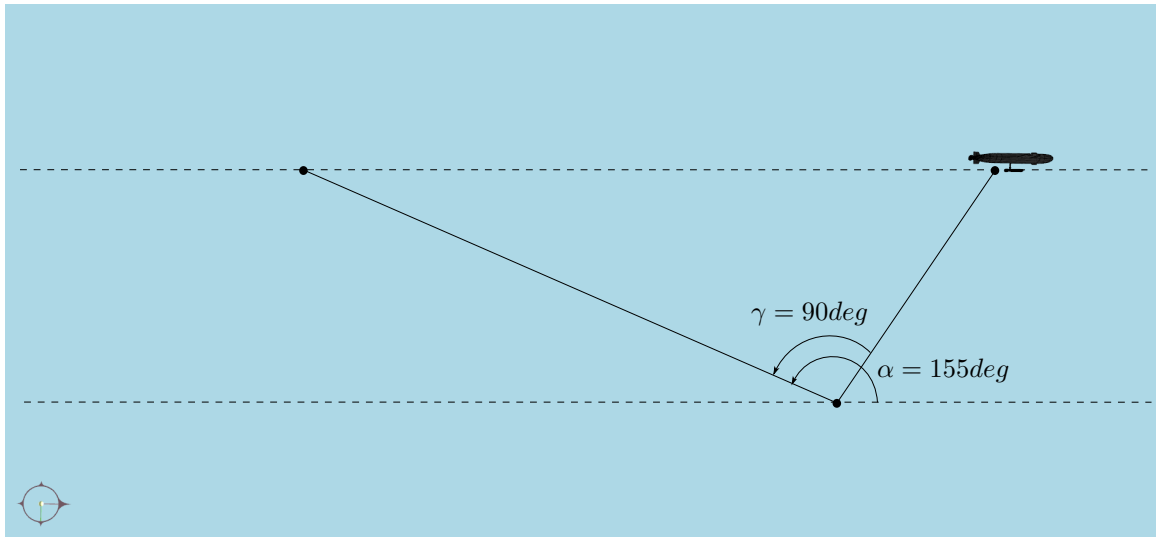| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 56: A screenshot of the simulation results taken at a time of around 375 seconds. UUV shown scaled 4x larger.

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4.9   Docking mechanism control (Stage 2)

The purpose of this test is to demonstrate the docking mechanism and its controller's ability to track and capture the UUV in non-optimal conditions. The simulation setup is identical to that found in Section 4.8 with the exception that the submarine, UUV, and docking mechanism are exposed to a single 2 m , 14 second period Airy wave travelling in the opposite direction as the submarine's heading. This causes relative heave and surge motion between the UUV and submarine which the docking mechanism must compensate for.

The entire docking simulation (stage 1) is completed. However, only the results where the submarine's PSSs can sense the UUV is presented. The presented simulation results begin with the UUV about to enter the docking envelope and Stage 2. The UUV will be travelling slower than the submarine thus it will be slipping back toward the docking mechanism's actuation plane. As the UUV nears the actuation plane, it will increase its speed proportionally to its distance from the actuation plane such that when it enters the actuation plane it is travelling at or near the same speed as the submarine.

The positioning system sensors are mounted to the docking mechanism's first link as shown in Figure 57. Their reference frames are oriented with their $\hat{x}$ axis pointing to starboard, $\hat{y}$ axis pointing to the stern and their $\hat{z}$ axis pointing down when the docking mechanism is perfectly horizontal. The `MDC` and `PlanarActiveDockController` account for PSS' reference frames when trying to capture the UUV.
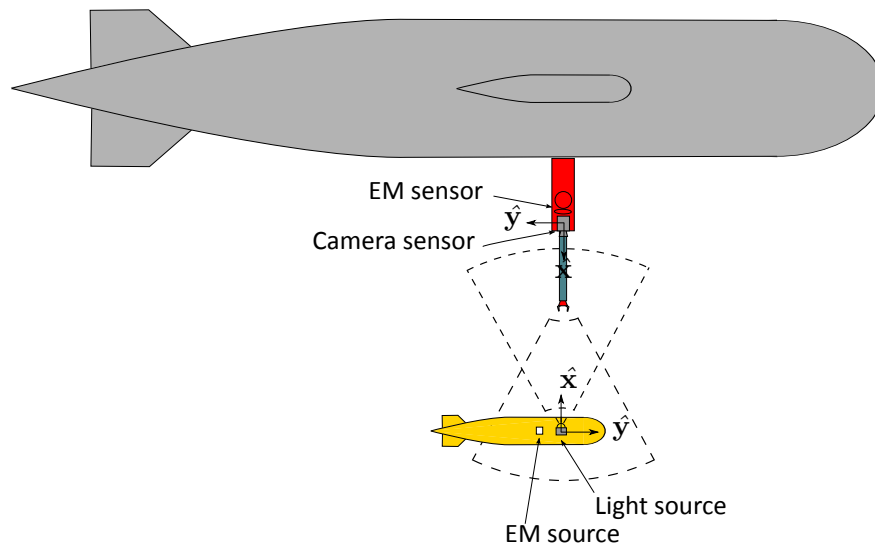

Figure 57: The optical and EM positioning system reference frames.

4.9.1   Simulation Results

Figure 58 shows details of the docking mechanism orientations during stage 2 of the simulation. It shows that shortly after 400s, the UUV enters the docking envelope, and the docking mechanism begins tracking the UUV. This can be seen when the docking mechanism's roll DOF θ_1 begins varying to follow the UUV. This also indicates that before stage 2 began the wing fairing's pitch maintained a dock roll of 0 degrees. After stage 2, the wing fairing's pitch varies to track the UUV in space. Also shown is the local angle of attack of the wing fairing at mid span. The angle of attack stays within a 10 degree window.

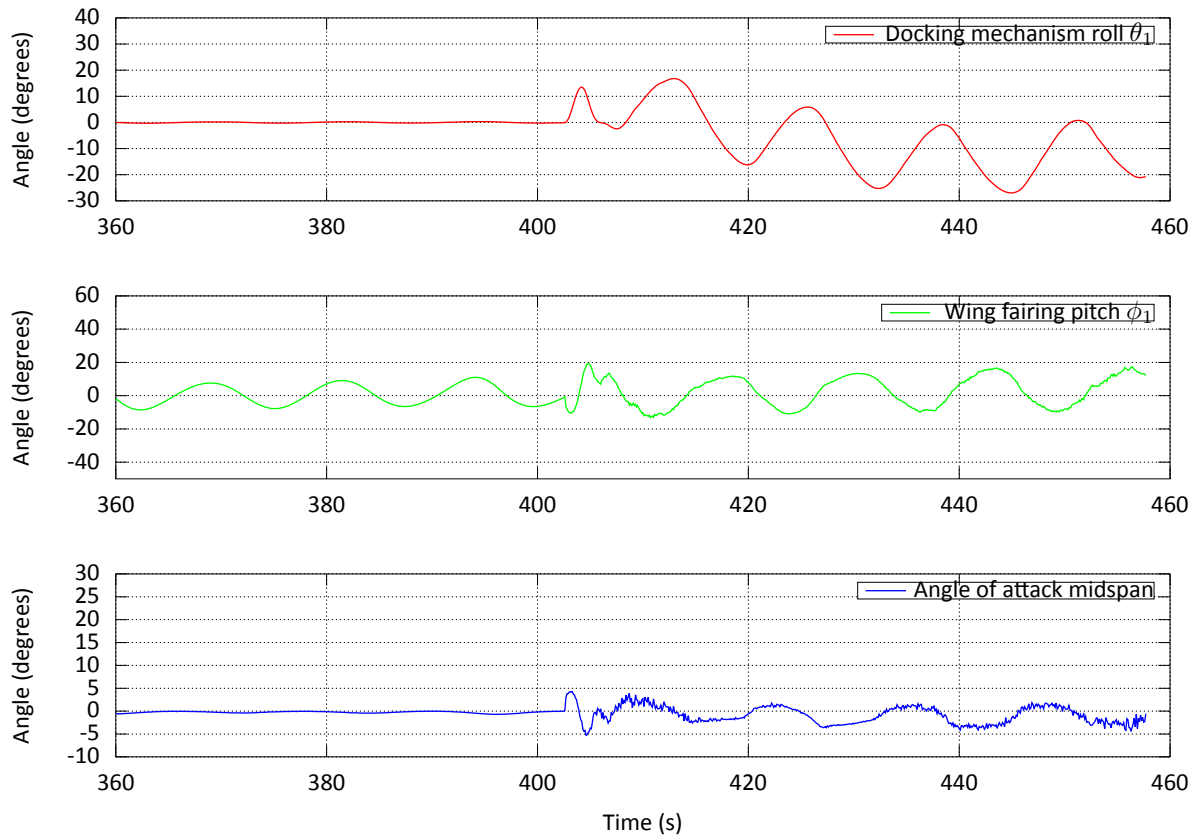| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 58: The docking mechanism's roll degree of freedom θ_1, wing fairing pitch ϕ_1, and the angle of attack of the actuated wing fairing as a function of time for stage 2 of the docking procedure.

When the UUV enters the docking mechanism's actuation plane, the docking mechanism's prismatic joint actuates to make contact with the UUV. This reduces the distance between the end effector and the UUV's capture point to near zero. This contact is considered a successful capture. Figure 59 shows the relative position measurements made by the fused and filtered short range EM and optical positioning systems signals. Also shown is the total distance between the EE and the UUV source as measured by the PSS, but corrected for the position of the EE.

The lateral distance between the sensor, mounted on the first link, and the source on the UUV is represented by the $\hat{\mathbf{x}}$ component signal. The distance between the PSS sources on the UUV and the docking mechanism's actuation plane is represented by the $\hat{\mathbf{y}}$ component of the signal. A negative value corresponds to a position in front of the actuation plane due to the sensor frame's orientation. Its magnitude reduces from a value of around -5m at the start of stage 2, at a time of 403s, to a distance of -1.5m, the $\hat{\mathbf{y}}$ distance the docking mechanism is asked to capture the UUV. The $\hat{\mathbf{z}}$ component of the relative position measurement is a measure of the misalignment of the dock and the UUV. It remains very near zero for the duration of stage 2 even if the UUV and submarine are oscillating relative to each other. This shows that the actuation of the wing is able to control the dock and keep it pointed toward the UUV for capture. When the prismatic joint is actuated to capture the UUV at a time of 419s, the distance between the EE and the PSS sources on the UUV drops to near zero.

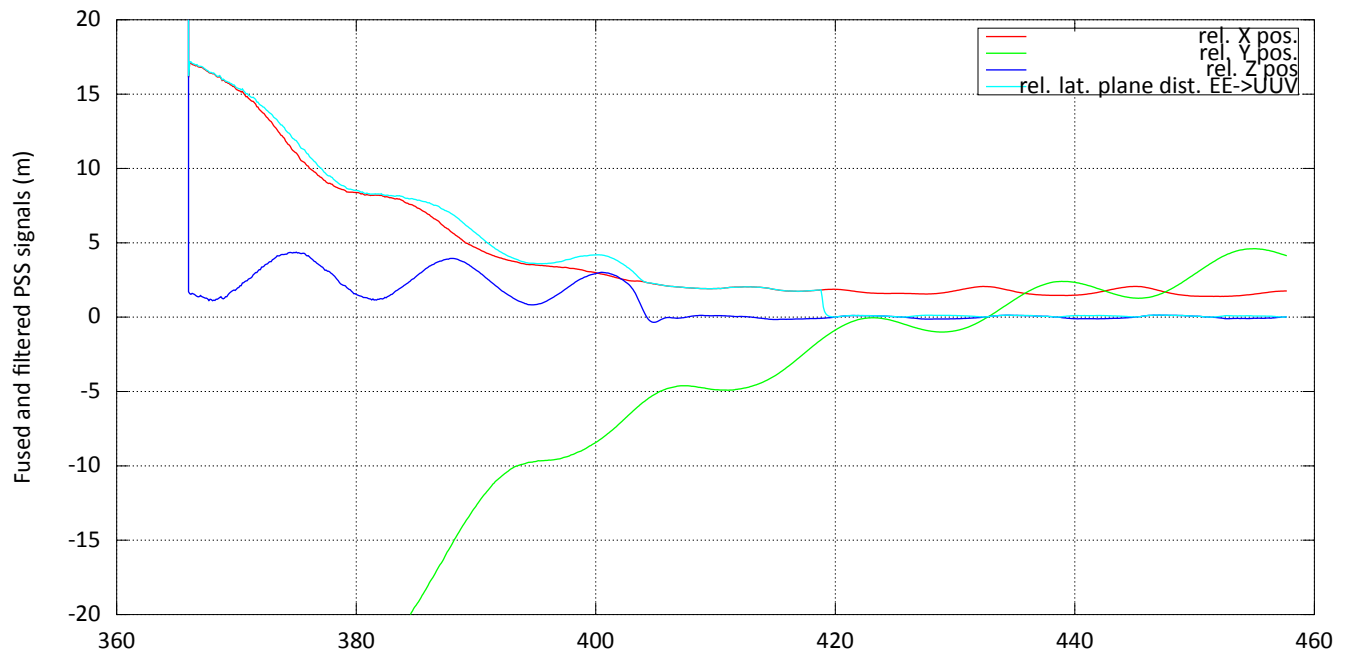| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 59: The fused and filtered PSS signals.

Figure 60 through 62 show screenshots of the simulation visualisation. Figure 60 is a screenshot taken at a simulation time of around 407 seconds, the UUV is ahead of the actuation plane and is slowly slipping back. Figure 61 is a screenshot taken at a simulation time of around 418 seconds where the UUV almost in the actuation plane and continues to slip back though is accelerating to try and match the speed of the submarine. Finally, Figure 62 is a screenshot taken at a time of around 424 seconds; the docking mechanism has made contact with the UUV for capture, completing the simulation.

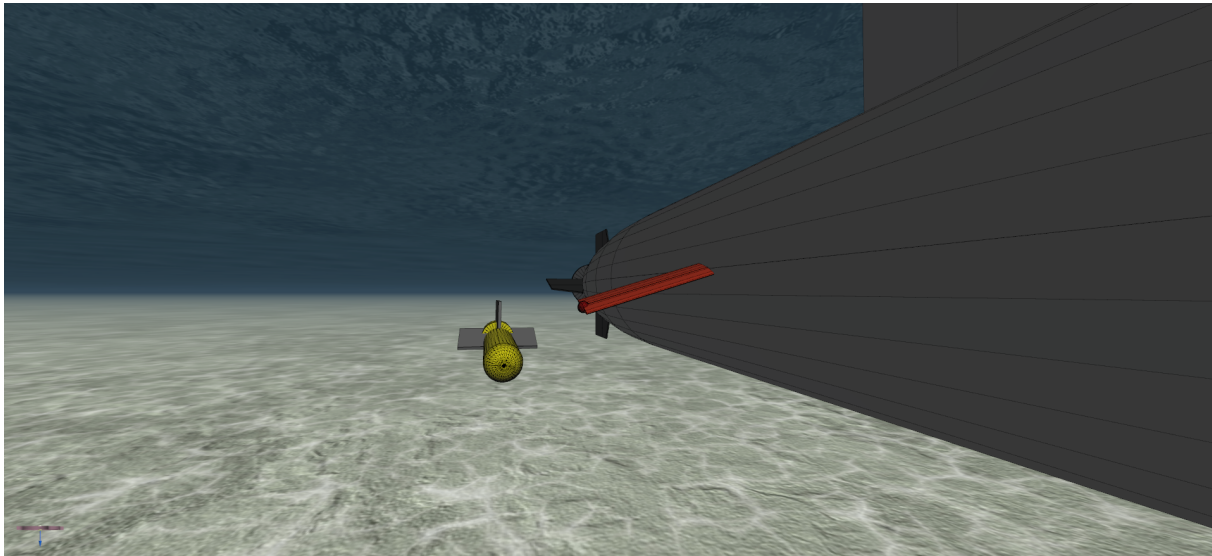| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 60: A screenshot of the simulation results taken at a time of around 335 seconds.

Figure 61: A screenshot of the simulation results taken at a time of around 343 seconds.

4.10   Wing dock performance simulations

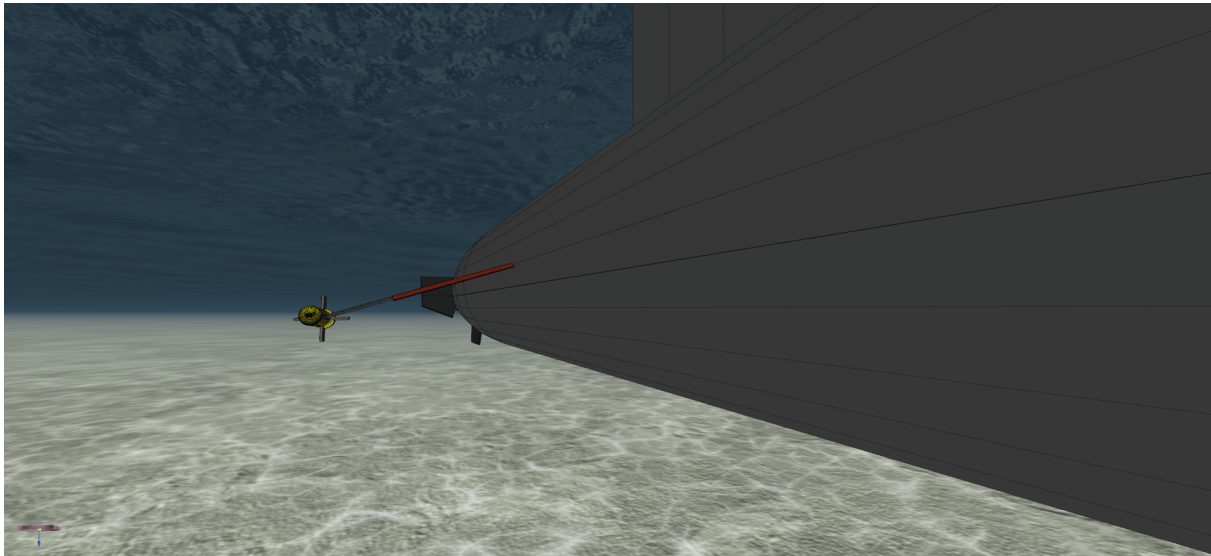| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 62: A screenshot of the simulation results taken at a time of around 352 seconds.

4.10.1 Overview

The ability to capture the UUV depends on the docking mechanism's ability to make precise contact with the UUV. Placing the end-effector on the capture point of the UUV requires the docking mechanism to have tight control of its roll degree of freedom in particular. The UUV controls longitudinal motion with its thruster and maintains its heading and depth while the docking mechanism controls both transverse DOFs by actuating its roll joint DOF and prismatic joint DOF. The most difficult DOF to control is arguably the docking mechanism's roll which must overcome oscillating fluid forces from waves. Roll angles as small as +/- 2degrees can translate to transverse motions as large as +/- 15cm for a fully extended prismatic link.

To show how well the wing dock design performs, two rough sea test conditions were simulated. The simulations occurred in short crested head seas modelled using a JONSWAP wave spectrum. The first simulation has sea-state 4, on the World Meteorological Organization sea state code, where the waves have a significant wave height of 2m and peak period of 13s. The 2nd simulation takes place in sea state 6 where the waves have a mean height of 5m and a peak period of 13s. The simulations have the submarine travelling at a average speed of 2.37m/s. Results are presented in Section 4.10.2 and 4.10.3.

The goal of these simulations is for the docking mechanism to maintain a roll angle θ_1 of 0 degrees.

4.10.2 Sea-state 4 Wing Dock performance

For this simulation, the submarine's autopilot maintains an average forward speed of 2.37m/s, as shown in Figure 63, as it travelled through the waves. For this case, the wing is able to control its roll degree of freedom to within about +/-0.3 degrees as shown in Figure 64. While controlling roll, the wing never exceeds AOAs (measured at midspan) of +/-5 degrees as shown in Figure 65. If the wing exceeded stall conditions (≈ 12 degrees) increasing the pitch angle would lead to a reduction in lift force. The PID controller would be unable to maintain control over its roll DOF until AOAs dropped to below stall again. This preliminary investigation indicates that docking is in the realm of feasibility for this sea state and at this forward speed.

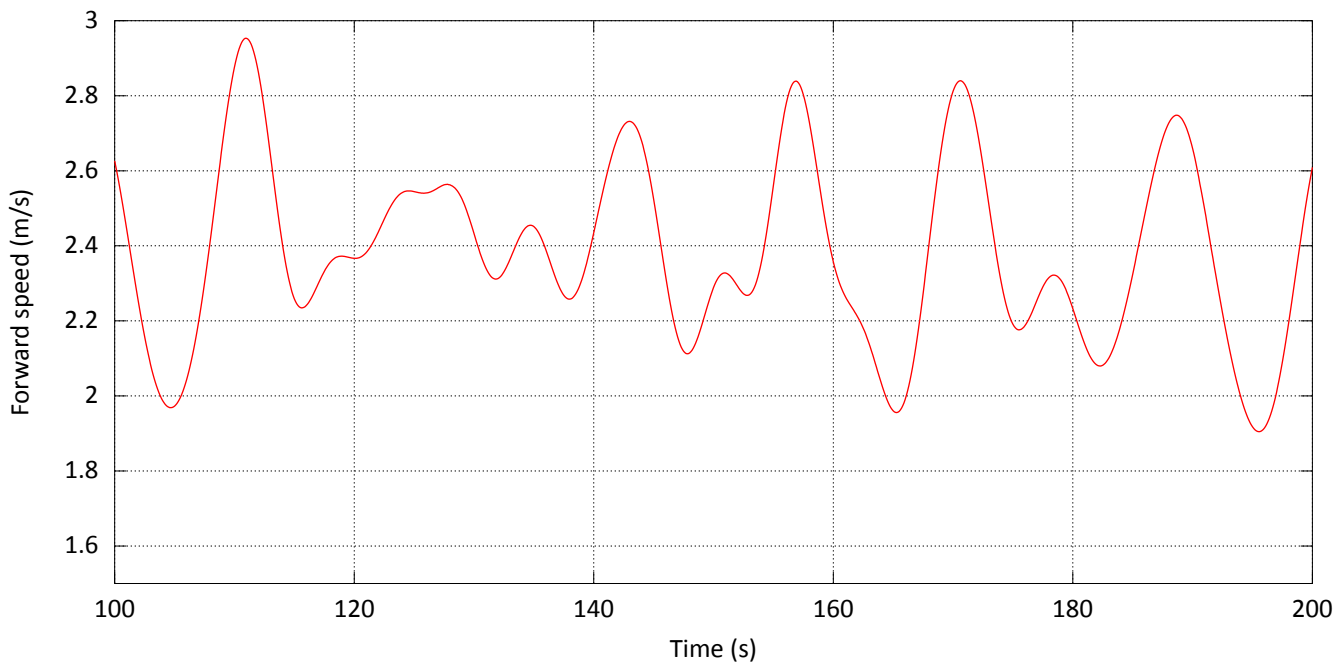| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 63: The submarine's forward velocity during the sea state 4 wing dock performance test.
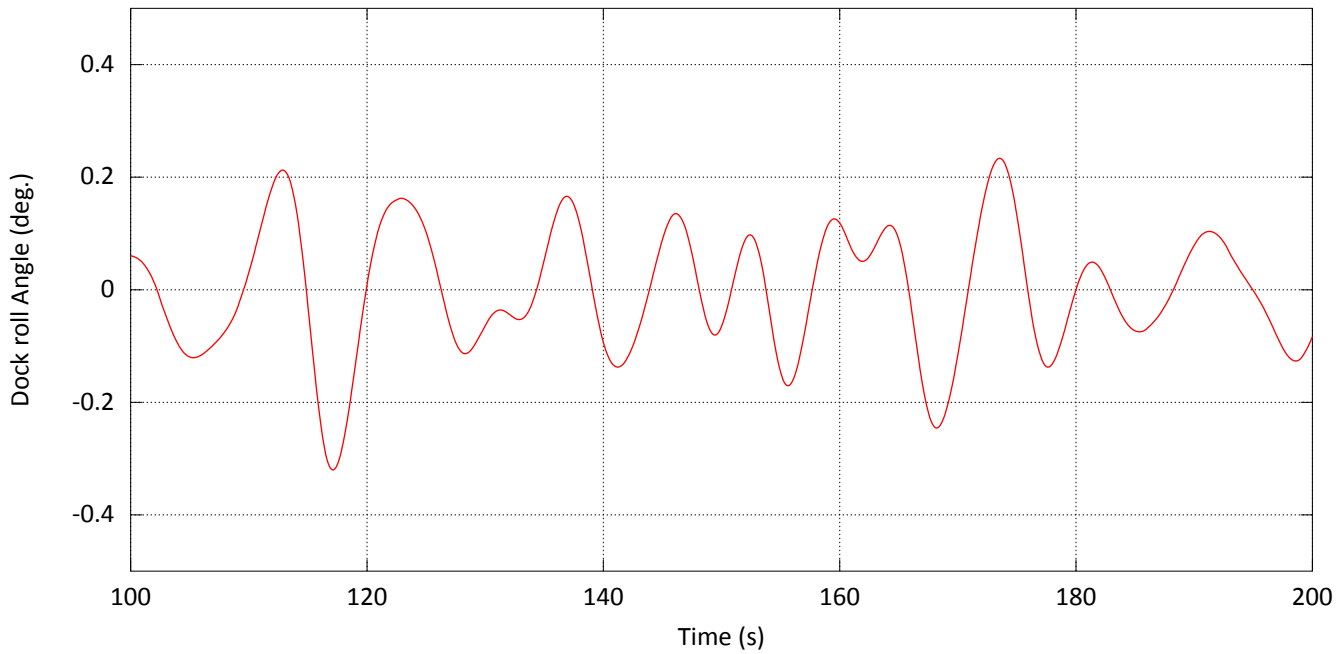

Figure 64: The wing dock's roll joint displacement during the sea state 4 wing dock performance test.

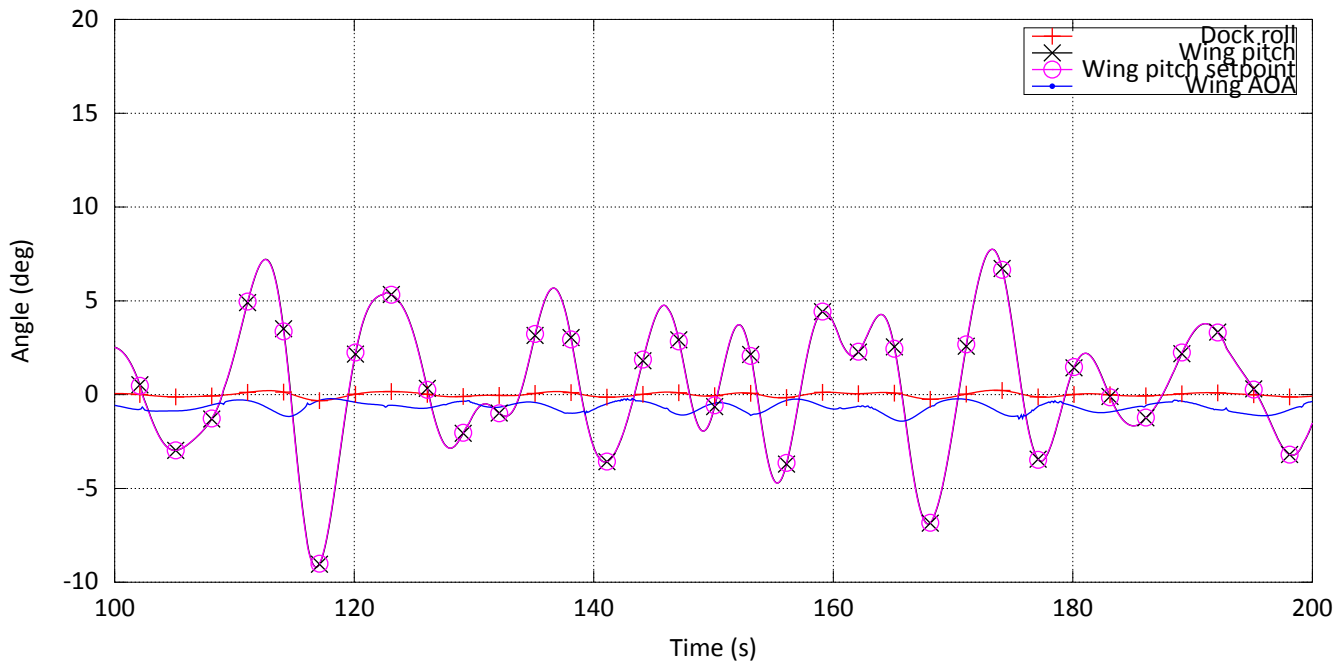| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 65: The wind dock's roll joint deflection, wing pitch deflection, commanded wing pitch deflection and midspan AOA during the sea state 4 wing dock performance test. Wing deflection and wing deflection setpoint match very closely.

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4.10.3   Sea-state 6 Wing Dock performance

For this simulation, the submarine's autopilot maintain an average forward speed of 2.37m/s, as shown in Figure 66, as it travelled through the waves. For this case, the wing is able to control its roll degree of freedom to within about +/-1 degree as shown in Figure 67. While controlling roll, the wing did not exceed AOAs (measured at midspan) greater than +/-5 degrees as shown in Figure 68. In real life, the wing would stall and have a difficult time maintaining control over the wing's roll, at least with a PID controller. This preliminary investigation indicates that docking is in the realm of feasibility for this sea state and at this forward speed.
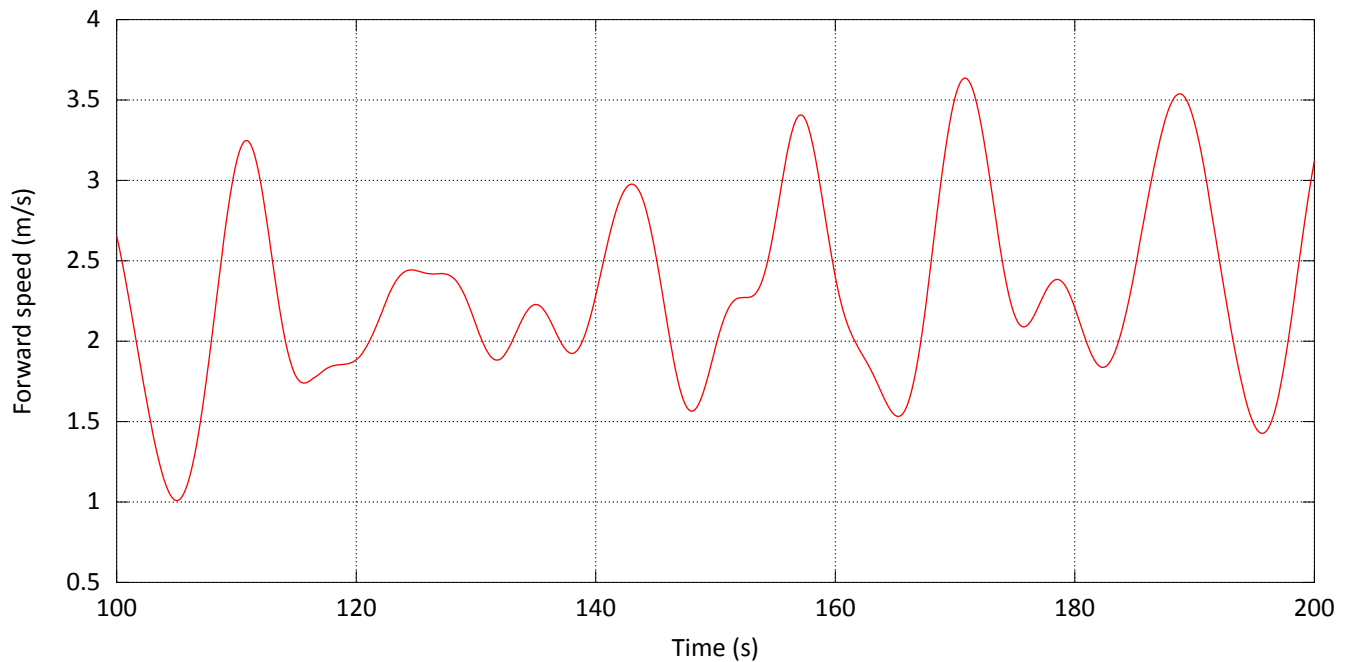

Figure 66: The submarine's forward velocity during the sea state 6 wing dock performance test.

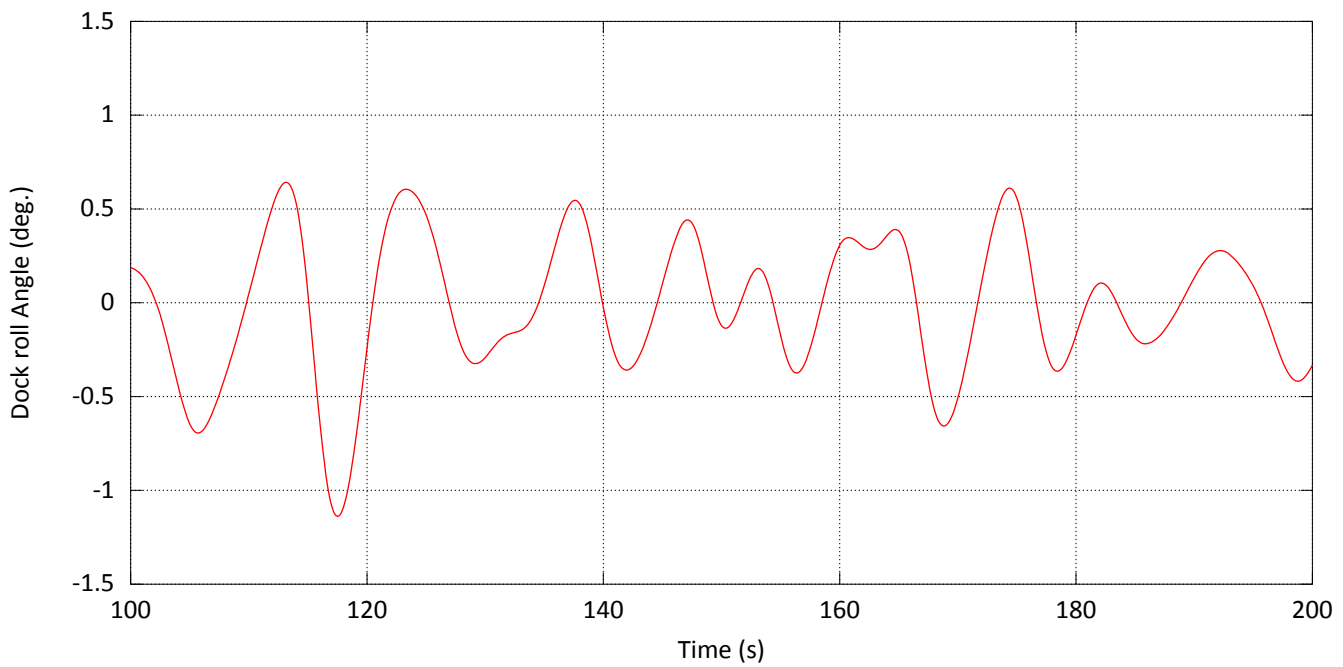| Title	Dynamic simulation of the automated docking of a UVV to a slowly moving submarine in littoral conditions: Sensor and control system modelling		
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Figure 67: The wing dock's roll joint displacement during the sea state 6 wing dock performance test.
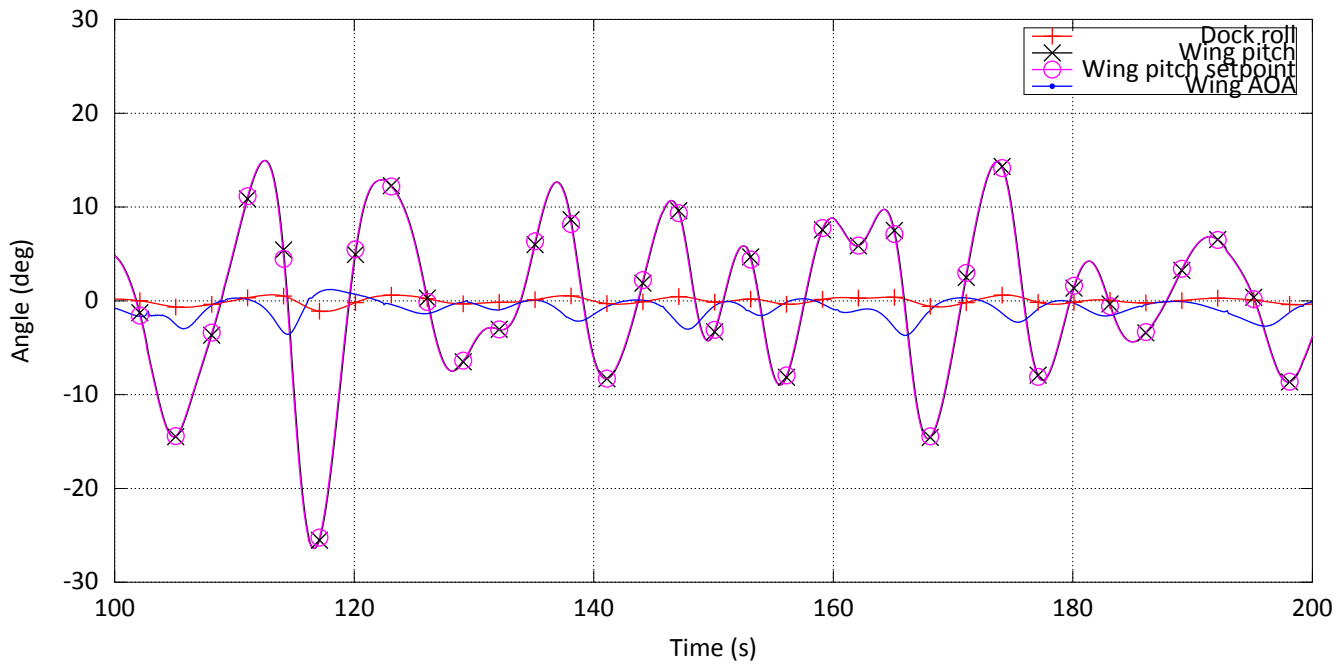

Figure 68: The wind dock's roll joint deflection, wing pitch deflection, commanded wing pitch deflection and midspan AOA during the sea state 6 wing dock performance test. Wing deflection and wing deflection setpoint match very closely.

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4.10.4 Discussion

The ability of the wing dock to control its roll position is dependent on what the maximum transverse loads the wing fairing can generate. Increasing the forward speed of the vehicle has the benefit of increasing the wing's maximum lift loads. Increasing forward speed will also reduce the required angles of attack required to control the docking mechanism. This incidence angle sets the lift direction which should be kept as vertical as possible to maximize the transverse loads.

The required AOAs can also be reduced by making the wing dock as light as possible. The more mass the dock has the higher the hydrodynamic loads need to be in order to achieve the same roll acceleration. Thus when designing the docking mechanism, its mass should be kept to a minimum.

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5 Conclusion

Over the course of this project a fully functional prototype simulation of a UUV docking with a submerged submarine was produced. A generic and flexible software infrastructure for building marine vehicle autopilots and control systems has been created. This allows a user to develop autopilot modules with any number of input or output channels and connect sensors or appendages to any respective input or output channels.

Basic PSSs have been implemented and used to develop demonstrative recovery simulations. Some verification tests were conducted which demonstrated the proper functioning of the control system component models. It was shown through the prototype simulation that the docking mechanism could feasibly perform both phases of a docking scenario and make contact with the UUV.

The docking mechanism's ability to control its end effector in waves depends on the actuation forces required. These forces can be obtained by increasing the required AOA or increasing the relative fluid speed. If the wing exceeds an AOA higher than 10-12 degrees, the wing is likely to stall and the current PID controller would fail to effectively control the end effector.

The control system modelling objectives of this project were met. What was created is a prototype simulation that serves as a proof of concept for a means docking a UUV to a slowly moving submarine. The concept has proven so far to be feasible. Much work remains to be done prior to the creation and testing of a real world prototype. Virtual prototyping via computer simulation is the most cost-effective way of testing and developing new designs, concepts, and controllers.

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6 Future work

This section presents a non exhaustive list of items that DSA has identified as potential areas for furthering the fidelity of the computer simulation. The 2nd part of this document, the hydrodynamics report, will contain it's own recommendations for future work. Here is the list, in no particular order:

- Design a real-world docking mechanism and use its inertia properties to model the wing dock in simulation

- Improved control the submarine bow planes for improved heave control

- Employ Kalman-filter to improve sensor fusion.

- Model errors in INS

- Improve PSS models

- Improve control schemes for controlling the docking mechanism.

- Modelling of the capture mechanism itself and model/simulate the capture.

- Import in DSSP submarine and UUV manoeuvring models.

- Incorporate fault tolerance in the control in the control system, for example, using MOOS software.

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Unmanned underwater vehicle docking, submarines, computer simulation