U.S Coast Guard Boat Launch and Recovery Task at NASA Ames Vertical Motion Simulator

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The Boat Launch & Recovery (BLR) experiment was a collaboration between the U.S Coast Guard and NASA. It took place at the Vertical Motion Simulator (VMS) from July 2017-October 2018. The experiment goals were to (1) prove the VMS can accurately simulate the motion of off-nominal sea conditions and to (2) collect data for the U.S Coast Guard on human performance related to small boat operations. The experiment included a software math model designed around empirical boat position data; a replica boat section manufactured to incorporate real-world task elements; and means to collecting objective and subjective data on participants. The experiment tested 12 certified U.S Coast Guard crewmembers through a randomized test matrix of different sea conditions to determine the interaction of motion and task completion.

I. Nomenclature

$\vec{a}_{BCG}$	=	acceleration vector at Boat C.G.
$\vec{a}_{VMS}$	=	acceleration vector at VMS Rotational Center
$\vec{a}_{BCM}$	=	acceleration vector at Boat Crewmember position
$\vec{\omega}_{BCG}$	=	angular velocity vector at Boat C.G.
$\dot{\vec{\omega}}_{BCG}$	=	angular acceleration vector at Boat C.G.
$\vec{r}_{BCG\_VMS}$	=	position vector of VMS rotational center w.r.t Boat C.G.
$\vec{r}_{BCG\_BCM}$	=	position vector of Boat Crewmember w.r.t Boat C.G.
$\vec{r}_{VMS\_BCM}$	=	position vector of Boat Crewmember w.r.t VMS rotational center
$H(s)$	=	transfer function
ζ	=	damping factor
ω	=	frequency
K_{ro}	=	gain factor
$t_{success}$	=	time captured to mark success

II. Introduction

The U.S Coast Guard routinely uses the Over-The-Horizon (OTH-IV), a cutter deployed, rigid-hulled inflatable boat for rescue and law enforcement operations. Cutter refers to a Coast Guard vessel 65 feet in length or greater with accommodations for crew to live aboard and the ability to deploy smaller boats including the OTH-IV. A deployment method is a davit system capable of raising or lowering the smaller boat with a crane from the side of the cutter. The crane suspends a specialized hook that connects to a lifting ring on the OTH-IV. Launching and recovering small boats involves several crewmembers, both aboard the cutter and the smaller boat. Crewmembers on the cutter operate the davit to control hook height and guide the small boat with towlines. The coxswain steers the OTH-IV so the last crewmember can grab the suspended hook and attach it to the lifting ring. The hook can weight 24-48lbs and manipulating it can pose a risk to the crewmember depending on sea conditions, level of fatigue, or task expertise. All crewmembers train extensively at sea and on land due to the inherent risk of the launch and recovery boat operations. Reliable tools are available to predict boat behavior during the launch and recover process, but avenues for predicting corresponding human performance during the task have been limited.

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In 2018, the U.S Coast Guard collaborated with NASA to utilize the Vertical Motion Simulator (VMS), a large-displacement flight simulator, located at NASA Ames Research Center, as a platform to test crewmembers in elevated sea conditions, otherwise known as sea-states. Specifically, the crewmember responsible with connecting the hook to ring. The experiment sought to demonstrate that the VMS could simulate elevated sea-states for the OTH-IV, which other land-based facilities could not. The simulation yielded objective real-time data, video recordings, and subjective survey data for each participant.

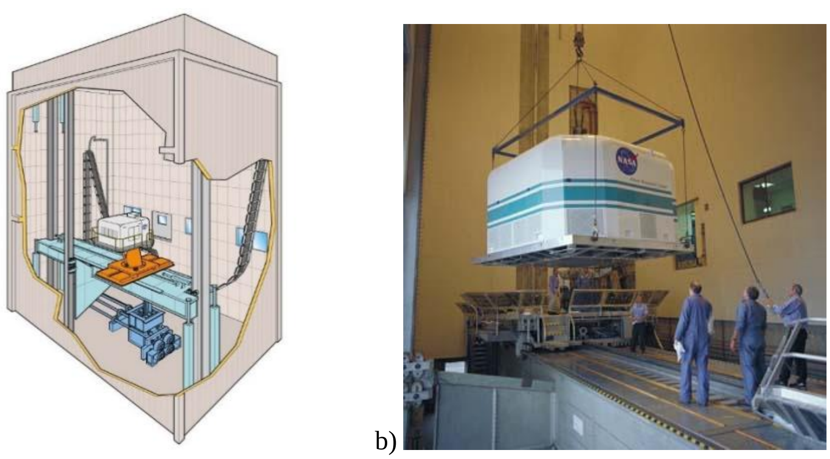
Between 2012 and 2017, U.S Coast Guard boat mishap reports stated of 1350 incidences thirteen occurred during small boat recovery. Mishaps can mean injury that results in a loss of a day's work, medical treatment beyond first aid, loss of consciousness, or material loss/damage valued above $5000. Eight incidences resulted in material damage, whereas four counted as injuries to crewmembers. Those injuries included falling overboard, pinched hand in hook, fall with knee injury, and a head impact with hook. An internal hazard and risk analysis aimed to identify and control potential injuries or material damage when simulating small boat recovery at the VMS.

Determining a safe operating envelope for this recovery task has been a challenge for the U.S Coast Guard. The goal of this experiment is to study human performance in a moving environment with a focus on task completion. A Motion Induced Interruptions (MII) is defined as an external motion causing a task interruption. Studies have analyzed the loss of balance of a static person in motion conditions to quantifying human interaction with their environment. In addition, fatigue related to sleep patterns has been found to affect U.S Coast Guard and Navy boat crewmember's performance. The U.S Coast Guard wishes to understand possible limits in human performance for small boat recovery. No published research on the performance of crewmembers regarding small boat recovery has been identified. Therefore, the results of this experiment at the VMS may benefit system design, operations and crew safety during severe recovery conditions.

III. Background

The Vertical Motion Simulator has been in operation since the 1980's and is a one-of-a-kind simulation research and development facility conducting studies and experiments involving some of the most challenging aerospace disciplines. The VMS is the largest vertical-displacement motion simulator in the world. The VMS facility supports full-motion, hexapod motion, and fixed-base (i.e., no motion) simulation. The VMS staffs engineers, technicians, and machinists to maintain a flexible architecture for simulation research. The VMS has investigated various types of aerospace vehicles throughout the years including transports, the Space Shuttle, fighter jets, and rotorcraft.

The VMS motion system is an electromechanical/electrohydraulic servo system capable of six-independent degrees of freedom. It is located in and specially constructed 73 feet wide by 36 feet deep by 120 feet high tower, and uses virtually the entire interior volume of this tower. Figure 1a shows the motion platform, which consists of a 40-foot long beam [blue] able to travels ±30 feet vertically. On top of the beam is a carriage [orange] that traverses the 40-foot length of the beam laterally. On top of the carriage is a gimbal system providing ±4 feet of longitudinal travel, ±18 degrees of roll and pitch and ±24 degrees of yaw.



a) b)

Fig. 1 a) Rendered cutaway of VMS tower, b) Installation of Interchangeable Cab (I-cab)

Interchangeable cabs (I-cabs) allow simulation of different vehicles with or without motion. The design flexibility provides visual environment, pilot inceptors, seats, displays and instrument panels to meet requirements provided by the researchers. Figure 1b shows an I-cab suspended from an overhead crane while being installed atop the gimbal system. Constructed cabs meet rigid mechanical, hydraulic and electrical interface specifications to achieve the desired interchangeability.

The structure of each cab is composed of four substructures: the base structure, the fixed canopy section, the removable canopy and the Image Presentation System (IPS) support structure. The base structure is a large flat weldment fabricated from aluminum channels, tubing and plate. It forms the floor of the cab and serves as the attachment to the motion system. Detachable front and rear sections facilitate transporting the cab between the fixed-base development area and the motion system. The fixed canopy section forms the rear wall of the cab providing a sturdy structure for mounting a number of items including cab lighting, sound system speakers, pilot observation cameras, head tracking support equipment and standard aircraft size equipment racks. The removable canopy section forms the front wall, sidewalls and roof of the cab and its primary functions are to enclose the equipment contained inside the cab and provide a sound/light barrier to prevent distractions to the pilot. The IPS varies markedly from cab to cab in Field-of-View (FOV) capabilities. Each IPS is tailored to a specific class of aircraft such as a helicopter, Space Shuttle, large commercial and/or heavy lift military aircraft, tiltrotor, or fighter jet. Lastly, each cab has removable floor panels and able to fit a wide range of pilot inceptors, seats, instrument panels, etc., from an inventory of aircraft simulation equipment.

IV. Experiment Design

The primary goal of the experiment is to focus on the relationship between sea-state motion and the single crewmember's task of connecting a suspended hook to the lifting ring onboard. The question posed is, at what sea-state do crewmembers fail to complete the task? Conditions such as sea-states are obviously difficult to isolate and quantify in the real world. By leveraging the VMS's large motion space and flexible architecture, the OTH-IV's response in varying sea-states can provide the Coast Guard with subjective and objective data from the boat crewmember. At the same time, the experiment design must incorporate repeatability and hazard controls for safety. The design of the experiment will simulate the crewmember at the bow of a small boat in elevated sea conditions. They must maintain balance while in motion and gain positive control of the hook before connecting it to the ring. A developed math model and procedures will ensure a repeatable and safe environment to investigate task performance.

A. Sea-state Profile

1) Large Amplitude Motion Program (LAMP): A program developed by the U.S Navy that generates multi-directional waves with a cosine squared spreading function, Bretschneider Spectra. Users can specify parameters such as wave height, speed of the boat, and other environmental factors. This results in a .csv formatted, time history profile of the boat's position. Each file was 400s long, sampled at 0.02secs, and contained data for all six-degrees (Surge, Sway, Heave, Roll, Pitch, and Yaw), evaluated at the OTH-IV Center of Gravity (C.G).

Table 1 Sea-state profile parameters

Sea-state	Significant Height (ft)	Modal Period (sec)	Heading wrt wave (deg)	Speed (kts)
3	2.9	7.5	0.0	6.0
4	6.2	8.8	0.0	6.0
5	10.7	13.0	0.0	6.0

2) Segmenting Profiles: Researchers preferred more variety in each sea-state. However, fewer motion profiles simplified the validation of the VMS motion. Six 180s profiles were generated by copying segments of the 400s file. This eliminated the chances of the participants predicting the profiles through repeated trials. Table 2 depicts how every 30s became a new start time for each profile. Motion ramped in over a period of 20s to full strength to avoid discontinuities in acceleration at the beginning of each trial. A simple script in Matlab split the full 400s profile into segmented profiles after specifying duration, offset, and number of profiles.

Table 2 Segmented sea-state profiles

time (s)	30	60	90	120	150	180	210	240	270	300	330	360	400
Wave motion files	180s profile_1 (30–180)												
		180s profile_2 (60–210)											
			180s profile_3 (90–240)										
				180s profile_4 (120–270)									
					180s profile_5 (150–300)								
						180s profile_6 (180–330)							
	400s profile (sea-state 3, 4, or 5)												

3) Coordinate Transformation: The VMS requires acceleration commands most commonly derived from equations of motion within a vehicle math model. Differentiated velocity and acceleration from the Boat's C.G (BCG) positions replaced the equations of motion. Figure 2 shows the coordinate transformation diagram relating Boat C.G, VMS Rotational Center and Boat Crewmember position. The transformed accelerations between Boat C.G and VMS Rotational Center serve as motion drive commands, represented in Eq. 1.

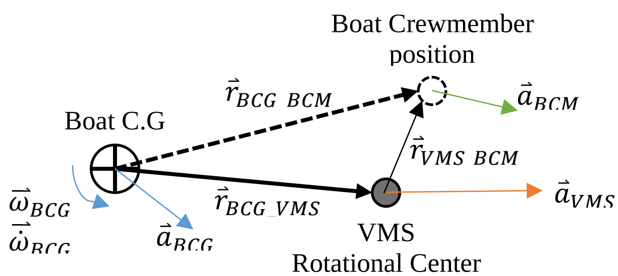
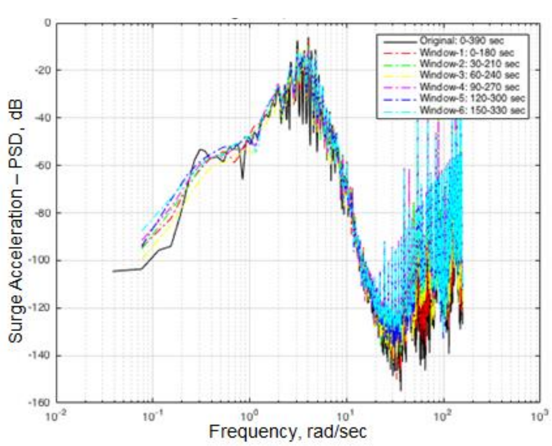


Fig. 2 Coordinate transformation diagram

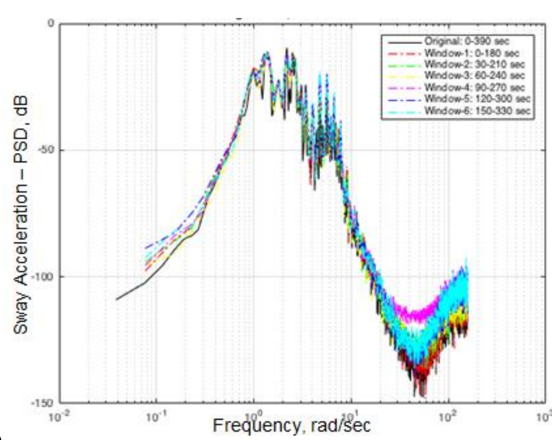
$$\vec{a}_{VMS} = \vec{a}_{BCG} + (\dot{\vec{\omega}}_{BCG}\ x\ r_{BCG\_VMS}) + (\vec{\omega}_{BCG}\ x\ \vec{\omega}_{BCG}\ x\ r_{BCG\_VMS}) \qquad (1)$$

B. PSD validation

The Power Spectral Density (PSD) was analyzed to verify the energy distribution between the original 400s motion profile and the 180s segmented profiles. The full 400s sea-state motion profile represents a spectrum of signal frequencies distributed over the time series. If the 180s profiles did not contain similar frequency distributions as the 400s profile, then the segments would need to. Figure 3a-f shows the PSD analysis of sea-state three acceleration command in all six degrees of freedom for the segmented motion profile.



a)



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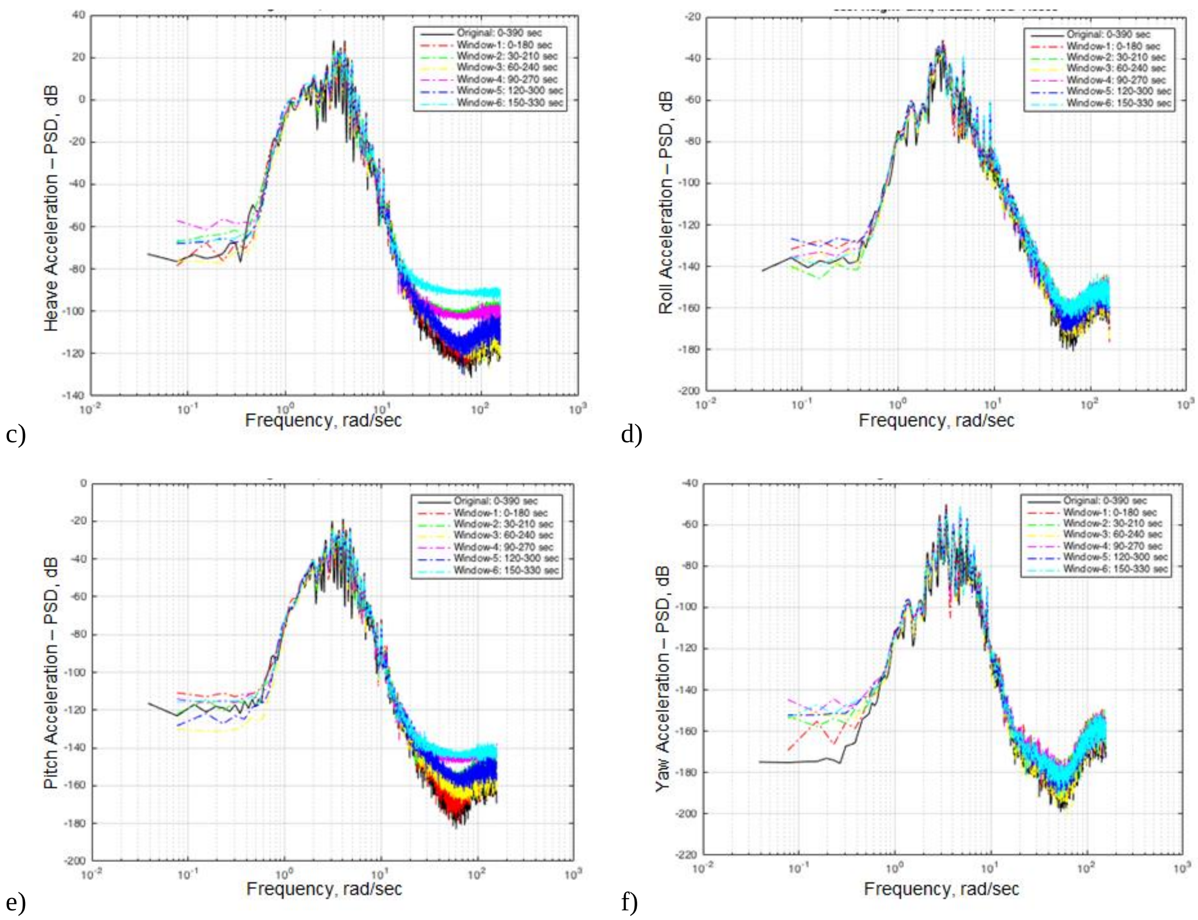

Fig 3 a) Surge acceleration PSD, b) Sway acceleration PSD, c) Heave acceleration PSD, d) Roll acceleration PSD, e) Pitch acceleration PSD, f) Yaw acceleration PSD

The plots confirm the segmented profiles show similar power spectrum to the original profile across the operational frequencies, but showed some discrepancy at frequencies below 0.4 rad/sec and above 20 rad/sec. The difference in the low frequency spectrum is due to the break frequency of the VMS' washout filter. The selected break frequency reduced the position drift of the simulator caused from the acceleration commands. The difference in the high frequency is likely due to the sample size (400s vs. 180s), thus a lower resolution in a smaller sample. Figure 3c – Heave acceleration, shows the largest difference at high frequencies, which is possibly due to the inertia of the simulator.

C. Cab and Hardware Modifications

The modifications to a cab and VMS procedures for this experiment are different from previous aerospace vehicle experiments conducted at the VMS. The recovery task requires the participant to stand as they would aboard the OTH-IV; gain control of a suspended hook and attach it to a lifting ring; all while maintaining their balance through sea-state motion. The design called for a cab with no front canopy, IPS structure, instrument displays, or pilot inceptors. Figure 4 shows the remaining platform with an OTH-IV replica bow section surrounding the participant. The bow section is an aluminum structure, capped with aluminum sheet metal, lifting ring and front seat. Padded foam covered hard surfaces and sharp edges as a hazard control.

The unrestrained nature of the task while in motion posed the great risk for participants. A harness system worn by the participant attached at four points prevented falls and allowed enough mobility to complete the task. Figure 4 shows three fixed length lanyards to prevent the participant from falling out of the bow section. A fourth self-retracting lanyard prevented the participant from falling down within the boat section. Additional polycarbonate sheeting installed on the perimeter rail kept would prevent anything from falling off the cab's platform.

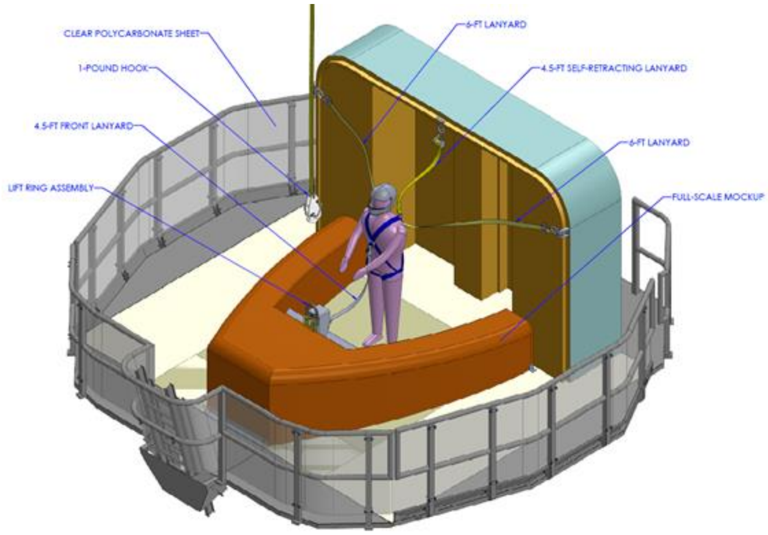

Fig 4   Modified I-cab layout

The suspended hook element had to address the possibility of it striking the participant. The overhead crane used to install the I-cab along with a fixed length cable suspended a hook similar to the arrangement in Fig. 4. A 24lb hook used by the Coast Guard posed too large a risk for a VMS experiment. Figure 5 shows a rendered model of the replica hook 3D printed out of plastic with a full-functional hinge and latch mechanism and aluminum handles. A magnetic breakaway disconnected the hook from the cable if the hook latched to anything while the cab was in motion. The magnet separated from an applied force greater than 16lbs. The result was a hook assembly that weighed one pound.

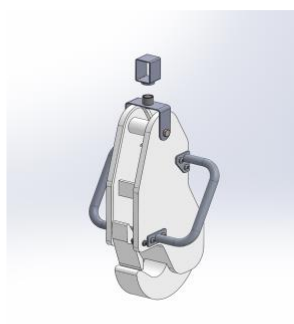

Fig 5   Rendered 3D printed davit hook with magnetic breakaway

The one-pound hook constraint came from regarding orbital debris because the VMS has no data regarding this type of hazard. *"Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 Joules…"* (NASA STD 8719.14B)

Figure 6 is a contour plot representing kinetic energy given speed and weight of an object. The green region depicts the acceptable design kinetic energy. The red region represents mass/speed combinations greater than 15 Joules of impact energy. The design speed of impact was determined to be 26.9 feet per second, which represents the worst-case scenario. All six axes would achieve a maximum speed and meet a swinging hook with a speed of 5 feet per second to get 26.9 feet per second.

NOTE: To date the VMS has never had an occurrence that resulted in a maximum speed in all six axes.

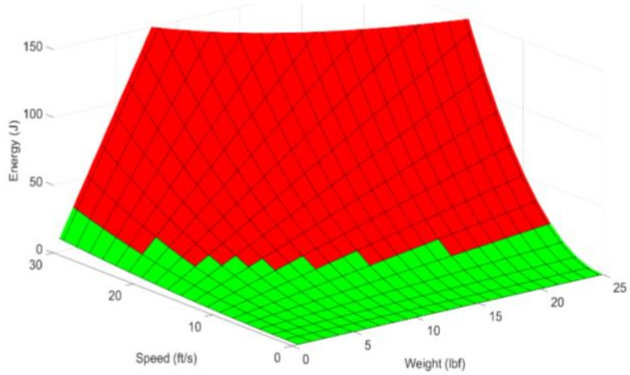

Fig 6 Kinetic energy contour plot

The weight reduction was an effort to limit the overall kinetic energy of an impact. Using the worst-case scenario as a speed constraint, a one-pound hook produces 15.25 Joules of energy. Table 3 shows kinetic energy for several objects including the 24lb hook the U.S Coast Guard actively uses. The impact kinetic energy for the one-pound is slightly larger than the NASA STD 8719.14 limit.

NOTE: NASA STD 8719.14 assumes an unprotected human.

Table 3 Kinetic energy comparison

Object Description	Speed (ft/sec)	Energy (Joules)
9mm bullet	1170	467
24-lb USCG lifting hook	26.9	366
100mph baseball	146	145
25mph softball	36.7	24.8
1-lb 3D printed hook replica	26.9	15.2

The last element to the recovery task required a modified lifting ring. Figure 4 shows the position of the lifting ring in the bow mockup. An installed sensor detected the hook and provided an analog signal to record the time of task completion. The MD-P18 sensor, as seen in Fig 7, is a photoelectric sensor from FSI Technologies. An adjustable threaded collar sets the height of the sensor to aide in calibrating the sensor. Calibrating the sensor to detect the hook at a distance less than three inches provided the most reliable response. If the sensor did not detect the hook, participants gave a verbal confirmation to record the event.

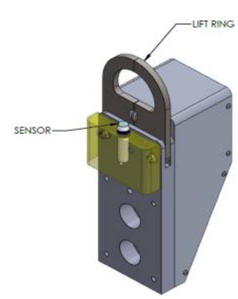

Fig 7 Rendered lifting ring

D. Math Model

The math model provided external control to the motion in addition to sea-state profiles. The accelerations driving the VMS did not guarantee the participant could reach the suspended hook much less attach it to the lifting ring. The overhead crane used in the experiment could not simulate the davit's operation. A feature of the math model summed external motion commands to the sea-state profile to raise the cab to the suspended hook. Analysis done for each sea-state profile determined if the hook would hit anything on the cab. Areas on the cab identified as "Keep-Out Zones" provided a constraint to the commands. The designed controller referred to as the "Virtual Winch Operator" generated the external commands. Another featured called "Park Mode" ramped out the motion once the participant successfully connected the hook to the lifting ring.

1) Keep-Out Zone: Despite the predictable wave patterns of the sea-state profiles, the math model needed to monitor and verify the position of cab relative to the hook. Figure 8 shows a visualization of the Keep-Out Zones overlaying the modified cab.

   - Zone 1 [green]: Surrounds the participant standing at the most forward position. The box dimensions are 4 feet wide by 2 feet deep and 1foot above the participant.
   - Zone 2 [blue]: Surrounds bow mockup in front of the lifting-eye. The trapezoid dimensions are 5.72 feet wide by 3.17 feet deep and 2.13 feet to 2.61 feet high measured from the base of the lifting ring.

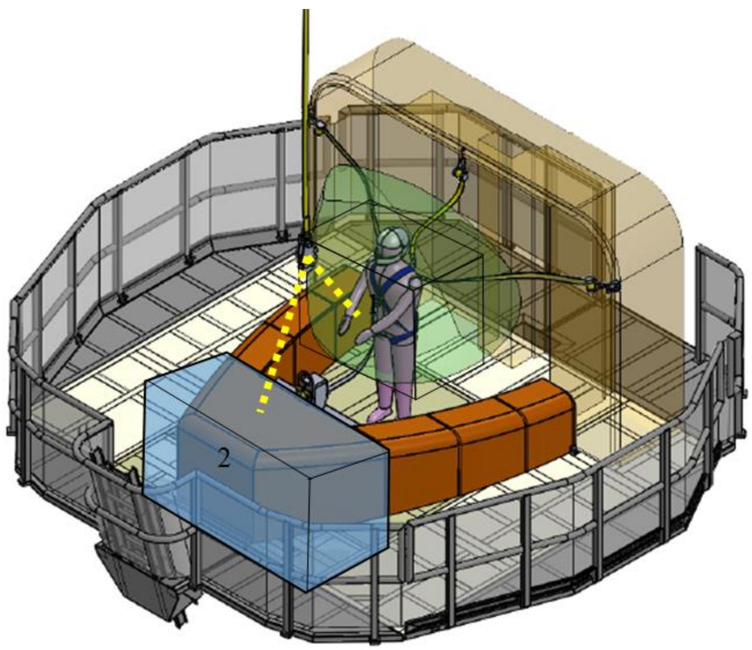

Fig 8 Visualization of Keep-Out Zones

Each Keep-Out Zone was comprised of eight points. The surfaces made up by four points was associated with a normal vector. Each surface measured a vector to the hook with a known height. The angle between the two vectors indicated if the hook would enter either of Keep-Out Zone. The analysis showed where external motion commands would eliminate any impacts

2) Virtual Winch Operator: Control applied to the forward-aft, side-to-side, and up-down directions positioned the hook close enough to the lifting ring referred to as an "Opportunity". The Virtual Winch Operator (VWO) generated motion commands to control the distance between hook and lifting ring for each sea-state profile. The VWO replaced need of a crane operator or a coxswain to steer the OTH-IV for this experiment.. The VWO command was a rate limited step input to a 2nd order low-pass filter resulting in an acceleration command. Equation 2 shows the 2nd order low-pass filter used to sum with the motion profile's acceleration commands upstream of the VMS' washout filters. The transfer function was applied in surge, sway, and

heave axes. A designed VWO profile unique to each sea-state profile provides a reliable method to control the distance between cab and suspended hook.

$$H(s) = \frac{s^2+2\zeta_{x,y,z}\omega_{x,y,z}+\omega_{x,y,z}{}^2}{s^2+2\zeta_{vwo}\omega_{vwo}+\omega_{vwo}{}^2} \qquad \zeta_{vwo} = 1.0 \qquad \omega_{vwo} = 1.0 rad/sec \tag{2}$$

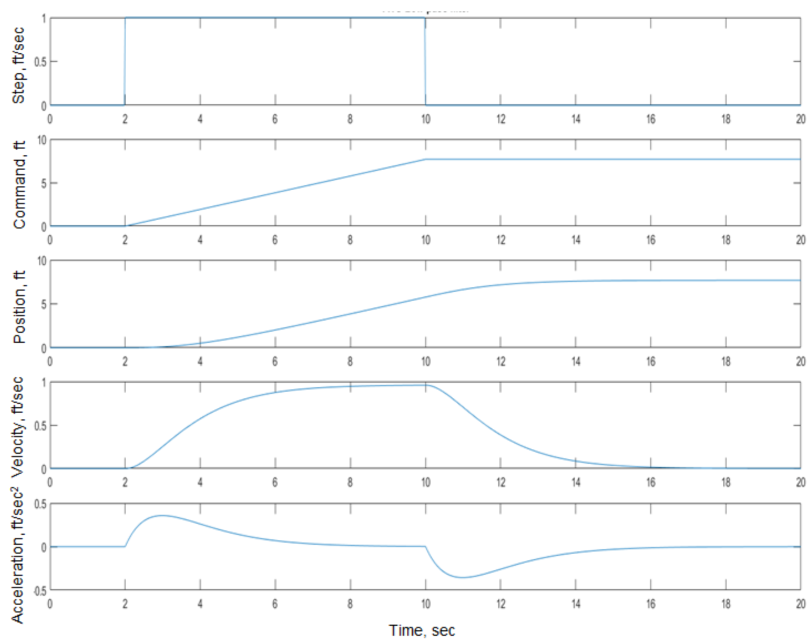

Fig 9 VWO 2nd order filter response

Figure 9 shows the results of the VWO step-input test in the surge axis. The Step signal represents the rate input which integrated to the Commanded position. The Position, Velocity, and Acceleration signals are the results of the 2nd order low-pass filter and the VMS' washout filter. The assumption was that the participant would not notice the VWO commands while focusing on the suspended hook in an elevated sea-state.

3) Park Mode: The last feature of the math model determined how the motion would ramp out upon task completion. Attempting to stop instantaneously could damage the simulator or injure participants, but allowing the motion to continue might damage the hook or other equipment. Therefore, a transition that does not exceed any simulator limits along with fail-safe hardware will be necessary to end one trial and prepare for the next. The Park Mode design approach:

- Capture the simulator height when sensor detects hook
- Level the simulator and ramp out any sea-state commands
- Raise the simulator above the capture height to create slack in the cable
- Rely on magnetic breakaways as a fail-safe

With no motion, the participant was free to disconnect the hook and prepare for the next trial. The simulation engineer reset the model and returned cab to the center position before the next sea-state. The transition from peak of wave to a level platform requires a smooth transition accomplished with a gain factor in Eq. 3. The approach zeroed out the acceleration commands over two seconds immediately following a success.

$$K_{ro} = 1.0 - 0.5 * (1.0 - \cos((time - t_{success}) * \pi/2) \tag{3}$$

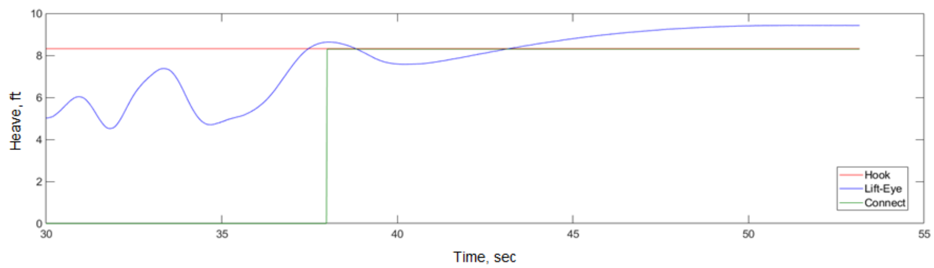

Fig 10 Heave position after Park Mode

Figure 10 shows the position of the lifting ring [blue] under motion exceed the height of the hook position [red] then the connection signal [green] triggered the Park Mode. The sensor activated at 38s once the participant connected the hook then the motion stabilized in 10s.

The approach achieved a great deal of repeatability and reduced the downtime between trials. As a precaution, a magnet breakaway joined hook and cable suspended from the overhead crane. At the end of most trials, the magnet broke away, but the cab raised enough for the participants to reattach the hook for the next trial.

E. Hazard and Risk Analysis

Safety concerns surrounding the standing nature of the experiment called for an internal review by the Human Occupancy Review Board (HORB). The board examined the harness system, emergency procedures, impact mitigations and personal protective equipment (PPE). By applying the procedure: identify, quantify and then mitigate to each hazard suited the safety requirements. The experiment collected the data while mitigating risk exposure to participants.

The Appendix section contains material referring to hazard analysis, severity and likelihood relationship, risk management categories, and control requirements. The following list describes the identified hazards and controls.

1) *Instability caused by high acceleration:* The participant can fall due to sudden motion and by standing without restraints. Properly trained personnel, fall-arrest equipment & PPE, or sea-state validation reduces the risk of instability. Final: M2

2) *Suspended hook contacts participant:* Impacts may occur if the participant is unable to avoid the hook due to high sea-state motion. The most unlikely scenario was analyzed and determined if the participant were hit in the head without PPE, they would be safe. Final: M3

3) *Suspended hook contacts platform:* A similar situation to HR-002, but with property damage. Verifying that the hook does not hit the platform with the VWO ensures no manage damage will occur. Final: L5

4) *Inadvertent hook motion:* A resultant of HR-002 or HR-003 would mean the hook was swinging with an un-deterministic trajectory to make problems worse. Final: M3

5) *Suspended hook connect to participant:* Similar to HR-002 but less likely because it involves the hook making a connection to the participant. Final: M3

6) *Suspended hook connect to platform:* Similar to HR-003 but less likely because it involves the hook making a connection to the platform. Final: L4

7) *Sharp edges or points:* Falls due to instability are exacerbated by hard surfaces or sharp edges. Foam covered surfaces and edges or the fall-arrest system restricted the mobility enough to protect participants. Final: M3

8) *Participant falls due to syncope*: In the very un-likely event that the participant were to pass out the fall-arrest system and the padded surfaces will mitigate injury. Final: M3

V. Experiment Operation

A. Test Matrix

Each sea-state and respective VWO profile was programmed to user input commands for the simulation engineer. Researchers tested each participant with an equal number of trials and sea-states through a randomized matrix of sea-state three, four, and five. Participants saw familiarization trials prior to data collection trials. Participants could repeat an attempt if an error occurred during the experiment.

Table 4 Daily Test Matrix

Familiarization	Data Collection
Park Mode Introduction	12 trials, 10min break
Sea-state 3 hook practice	12 trials, 10min break
Sea-state 4 hook practice	12trials, debrief

B. Data Collection

Time history data such as simulator position, velocity, and acceleration were collected at 50Hz saved as .csv formatted files. Researchers requested several camera angles to aid in post simulation analysis. Figure 11 shows the camera feeds all around the participant, to monitor MIIs for a given sea-state.

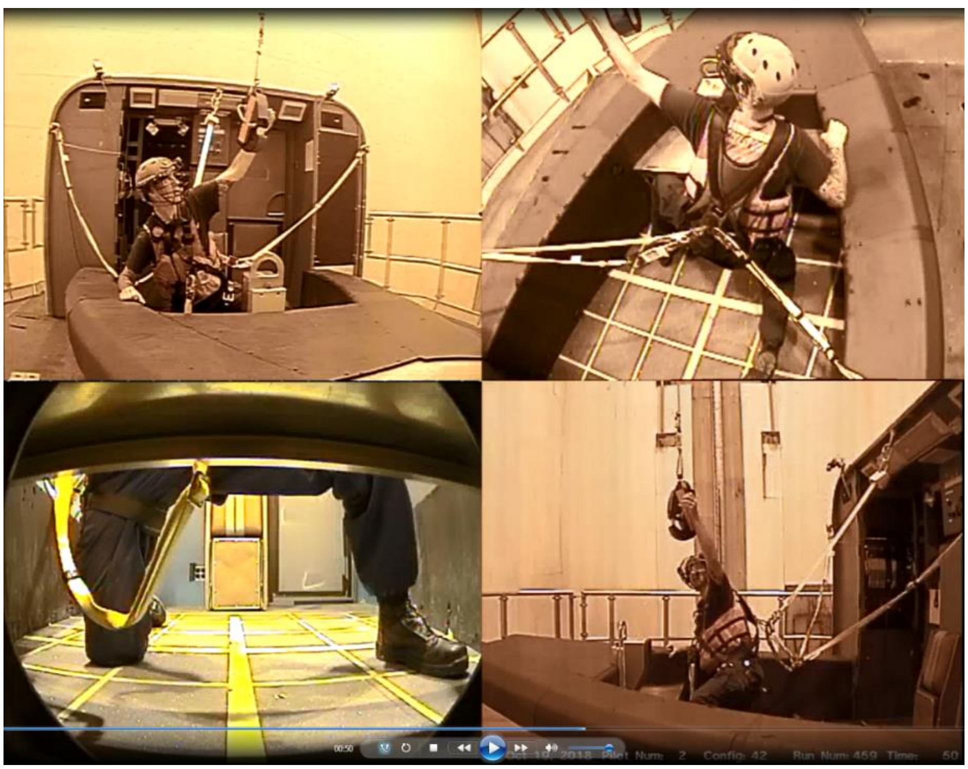

Fig 11 Video recording sample

C. Results and Discussion

Figure 12a-c shows the sea-state 5 profiles, the VWO signal, and hook position all evaluated relative to the lifting ring position. Figure 12d represents the distance between hook and the lifting ring. The hook position [red] is lowered to a known point at the start of each trial and reamins fixed in the surge and sway directions. The initial sea-state data [black dashed] had to be adjusted in each axes. Opportunities (Opps.) [green] happened when the hook and lifting ring were close enough to connect as seen in Fig. 12d. The final motion profile [blue] used by the VMS was the sum of initial sea-state data [black dashed] and VWO signal [magenta].

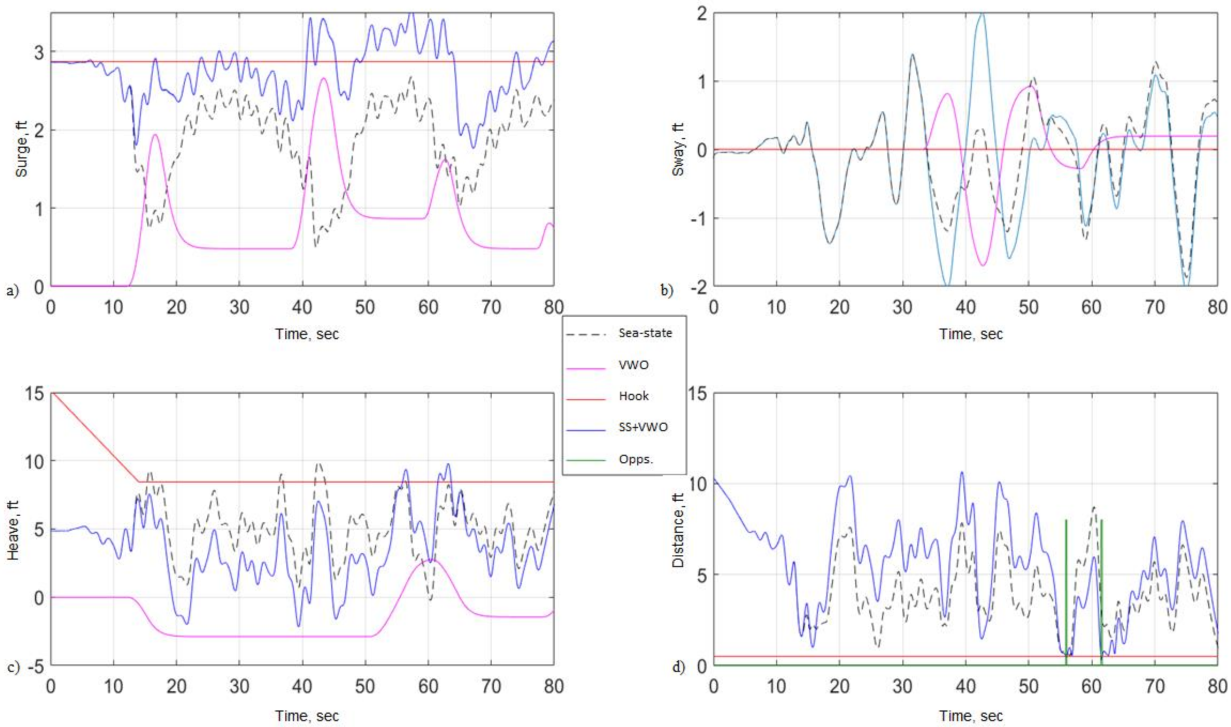

Fig 12 a) Surge position, b) Sway position, c) Heave position, d) Distance of sea-state 5 profile

The initial sea-state data in Fig. 12a shows the hook is too far to connect without the VWO commands. Figure 12c shows the sea-state data exceeds the hook height at 35s and 45s. Adjusting the heave profile with the VWO eliminated those collisions and created a better chance to connect hook. The goal was to position the lifting ring within six inches of the hook. Figure 12d shows the VWO created Opportunities to connect the hook at 55s and 62s. Therefore, the external commands generated by the VWO created opportunities and eliminated collisions for all sea-state profiles.

VI. Conclusion

Overall, the experiment collected data on 12 participants who displayed little trouble accomplishing the boat recovery task. Participants said that the wave motion was very accurate and saw the potential the VMS offered to studying OTH-IV boat operations. Subjective data and surveys revealed valuable information and suggestions on how to improve the simulation in terms of realism and fatigue effects. The simulation introduced artificial elements to the task such as a fall-arrest harnesses and a plastic one-pound hook, but participants reported that the harness did not affect performance and they understood the decision for the lighter hook. Artifacts like the motion ramp-out after hook connection did not resemble real-world task elements. However, participants did not report that motion ramp-out was a downside due to the complexity of the situation.

As the first boat simulation at the VMS, its successes include the implementation of a reliable sea-state model for the OTH-IV, hazard and risk analysis, and the data collection on certified participants. This first iteration set out to create a flexible system that can introduce more variety in sea-state profiles and collect useful information when analyzing hazards.

Appendix

A. Consequence and Likelihood:

Identified hazards will be classified according to the Consequence and Likelihood, as seen in Table 5. The urgency for resolution of a hazard is dependent upon the combination of the consequence and likelihood of each hazard, or the HAZARD RISK ASSESSMENT (HRA).

Table 5 Hazard Consequence and Likelihood

HAZARD CONSEQUENCE (SEVERITY)	
5	Catastrophic **Injury:** Loss of life, or permanent disability. **Property Damage**: Loss of facility, or direct cost of mission failure or property damage over $2M.
4	Critical **Injury:** Severe injury, or permanent partial disability, or hospitalization. **Property Damage**: Direct cost of mission failure and property damage between $500K and $2M.
3	Severe **Injury:** Moderate injury, full lost workday(s), restricted workday(s). **Property Damage**: Direct cost of mission failure and property damage between $50K and $500K.
2	Moderate **Injury:** Minor injury, medication or medical treatment administered. **Property Damage**: Direct cost of mission failure and property damage between $20K and $50K.
1	Minor **Injury:** Only first aid was administered or no injury. **Property Damage**: Direct cost damage less than $20K or occurrence or condition of employee concern where there is no property damage but possesses the potential to cause a mishap.

LIKELIHOOD (PROBABILITY)	
5	Very High; Likely to occur greater than: $\mathbf{10^{-1}}$
4	High; Probably will occur between: $\mathbf{10^{-2} < P \leq 10^{-1}}$
3	Moderate; May occur between: $\mathbf{10^{-3} < P \leq 10^{-2}}$
2	Low; Unlikely to occur between: $\mathbf{10^{-6} < P \leq 10^{-3}}$
1	Very Low; Improbable less than: $P \leq \mathbf{10^{-6}}$

B. Safety Risk Management Categories:

Per Ames Procedural Requirements 8000.4, the risk matrix shown in Fig. 13, referred to as a 'Stop Light Chart' for all hazard risk management. The demarcations between the risk rating levels (*Low* [green], *Medium* [yellow], and *High* [red]) are shown as a function of Likelihood and Consequence. Subscripts in parenthesis are a mapping of NASA-STD-8719.7; Facility System Safety hazard risk assessments.

C. Final Risk Acceptance / Risk Control Requirements

Low - Low Residual Risk: Low Residual Risk can be accepted by the Project after review, without Project Safety Review Board action.

Moderate - Moderate Residual Risk: Risk should be mitigated to an acceptable level. Moderate Residual Risk acceptance requires Project level acceptance with Project Safety Review Board concurrence.

High - High Residual Risk: Risk must be mitigated to an acceptable level. High Residual Risk acceptance requires a waiver. Risks rated as high require Project's PMC wavier approval.

Likelihood					
5	$L_{(3)}$	$M_{(2)}$	$H_{(1)}$	$H_{(1)}$	$H_{(1)}$
4	$L_{(3)}$	$M_{(2)}$	$M_{(2)}$	$H_{(1)}$	$H_{(1)}$
3	$L_{(4)}$	$L_{(3)}$	$M_{(3)}$	$M_{(2)}$	$H_{(1)}$
2	$L_{(5)}$	$L_{(4)}$	$M_{(3)}$	$M_{(3)}$	$M_{(2)}$
1	$L_{(5)}$	$L_{(4)}$	$L_{(4)}$	$L_{(4)}$	$M_{(3)}$
	1	2	3	4	5
	Consequence				

Fig 13 Risk Matrix (Stop Light chart)

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Computer Software
MATLAB and Simulink. R2017b ver. 9.3, 9.0. MathWorks 1 Apple Hill Drive Natick, MA 01760-2098