Evaluation of Head-Up Displays for Teleoperated Rendezvous & Docking

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***Abstract*—Rendezvous & Docking will be an essential part for many future spaceflight activities, like manned or unmanned exploration of the Moon or Near Earth Objects (NEOs), a Mars Sample Return mission, as well as On-Orbit Servicing or Space Debris Removal activities. While autonomy is expected to play a major role in future Rendezvous & Docking, human operators on the ground will still perform either real-time monitoring or actual control of the interceptor vehicle during its final approach. In order to enable the operator to perform these functions effectively and safely, a proximity operations Head-Up Display (HUD) was designed, providing attitude and trajectory prediction information in a number of different attitude projections, coordinate systems and display methods. The different configurations were compared in user studies to evaluate their performance in a number of test scenarios. The results show that an attitude HUD is a valuable addition to a teleoperation man-machine interface, with the outside-in attitude representation showing the greatest benefit for operator efficiency. The choice of coordinate system however has a small effect on the quality of target relative position estimates. Operators perform marginally better using a reference system based on the local horizontal plane than with one using the orbital plane. The different trajectory prediction display methods evaluated cause no measurable difference in maneuver guidance efficiency.**

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1. INTRODUCTION

Rendezvous & Docking[1] (RVD) is an enabling capability for many future space exploration activities, such as a Mars Sample Return Mission [1] or the further human or robotic exploration of Moon, Near Earth Objects (NEOs) or Mars. A flexible and adaptive RVD capability is furthermore quintessential for future On-Orbit Servicing (OOS) and space debris removal activities[2].

Automated RVD has been routinely practiced by the Russian Soyuz/Progress craft, the ESA Automated Transfer Vehicle (ATV) and the JAXA H-II Transfer Vehicle (HTV) on their supply runs to the International Space Station (ISS), and Mir and Salyut before that [2, 3]. Beyond space station operations, robotic demonstrator missions like ETS-VII, XSS-10 and -11, as well as Orbital Express have proven the technical feasibility of autonomous RVD and proximity operations in an OOS context [4–7].

However, on all these missions the target objects have to a certain degree been of a cooperative nature, mostly by having a stable attitude in space and by providing the approaching interceptor's Guidance, Navigation and Control (GNC) system with surface markings solely dedicated to the purpose of relative navigation [8]. In any OOS application within the environment of today's satellite population, the target objects will not be equipped with markings of that kind and will – in the case of space debris removal – probably be in a tumbling motion. RVD operations with these target objects will therefore be challenging for automated systems and will most likely require a high degree of human involvement. This can either be human monitoring and commanding in the case of *supervised autonomy* or actual real-time guidance and control in the case of *real-time teleoperation* (RTTO) or telepresence [9]. In any of these scenarios, the human operator must be provided with

[1] In this paper, the term "docking" is being summarily used instead of differentiating between "docking" and "capture & berthing".
[2] Space debris removal and On-Orbit Servicing will in this paper be summarized under the term "On-Orbit Servicing", since object maneuvering and de-orbiting can be classified as an OOS activity.

sufficient information to achieve Situation Awareness (SA). SA is defined as "[…] the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." [10]

For RVD and proximity operations, this means that the operator must be provided information about "his own" orientation and motion, as well as data regarding the motion in relation to the target, in order to be able to safely and efficiently monitor and command approach maneuvers. The essential knowledge about ownship motion is the current attitude in reference to an intuitively comprehensible reference system, as well as the future trajectory generated by maneuver commands. In order to provide this knowledge to the operator, an experimental proximity operations Head-Up Display (HUD) was designed and implemented.

This experimental HUD was used in our user studies to evaluate different methods of representing attitude data and display trajectory predictions. The main purpose of these studies was to identify the HUD configuration which will be implemented in the Third Eye situation awareness enhancement system (refer to section 7 and [11]), as well as to identify areas of interest for further research.

This paper provides a brief description of the design and implementation of the HUD itself (section 2), as well as the experiment setup (section 3). It then proceeds to provide the evaluation experiment results for the attitude HUD (section 4), the reference system comparison (section 5), as well as for the trajectory prediction HUD (section 6). Section 7 then describes to what extent the HUD is adapted reflecting experiment results and the requirements of the Third Eye situation awareness enhancement system. Finally, conclusions are given regarding the usability of different configurations of proximity operations HUDs.

2. The Proximity Operations Head-Up Display

This section provides a brief overview of the general design and implementation of the experimental proximity operations HUD used in the evaluation experiments [12].

The HUD provides both an attitude display and a trajectory prediction display. Different variants of attitude representations, coordinate reference systems and trajectory prediction displays are implemented for experimental use in user studies.

Attitude representations

The ownship attitude is represented as either an "inside-out" or an "outside-in" display (see Figure 1). With an inside-out display, the attitude scales are rotated around a fixed vessel symbol, reflecting the environment rotation from a pilot's point of view during a maneuver. In an outside-in display, a vessel symbol is moved within fixed attitude scales, to represent the vessel's motion from an observer's point of view [13]. Both representations have been shown to have advantages and disadvantages in aviation and underwater robotics [13, 14], but to the knowledge of the authors have

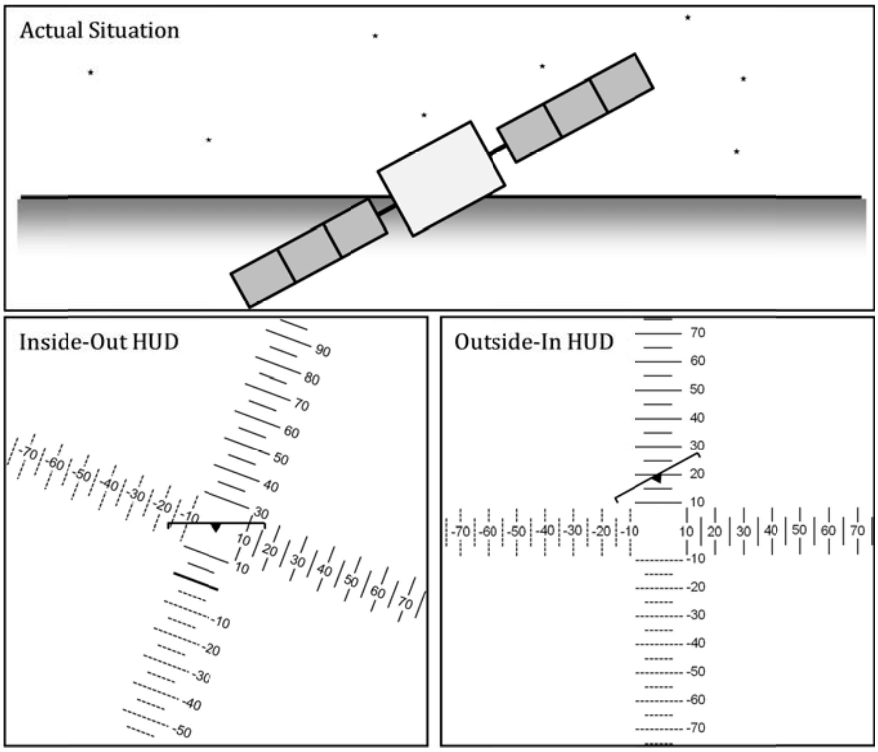


Figure 1 - Inside-out and outside-in attitude representations

not been tested in space telerobotics.

Coordinate Reference Systems

The proximity operations HUD provides three reference coordinate systems, based on the orbital plane, the local horizon, and the direction vector of the target.

In the orbit reference system the reference plane against which pitch and roll angles are measured is the orbital plane. The reference x axis and therefore both 0° yaw and 0° pitch is the direction of flight (which coincides with the orbit tangent for circular orbits). The y axis points radially towards Earth, the z axis completes the right-handed coordinate system.

The reference plane of the horizon reference system is the local horizontal plane, the x axis is again defined by the direction of flight. The z axis is pointing radially towards Earth, the y-axis completes the coordinate system.

The docking reference system is designed for close-range proximity operations and final approach, when the target is the main reference for navigation. Its principal x axis therefore points along the interceptor-target vector, which along with the interceptor body y axis (pointing along the left spacecraft wing) defines the reference plane. In this reference system, no roll angles can therefore be measured.

In all reference systems, the pitch angle is positive for "upward" pitching of the spacecraft, roll and yaw are both positive in clockwise direction.

Trajectory Prediction Displays

In order to allow the operator to understand the effect his guidance commands have on the relative trajectory of the spacecraft, three versions of a trajectory prediction display are provided. This is of particular importance for teleoperated maneuvers under the impact of time delay. The trajectory itself is forward-propagated using the Clohessy-Wiltshire (CW) equations [15].

This approach restricts the usability of the HUD system to near-circular orbits and quasi-impulsive maneuvering. This restriction is acceptable for the studies conducted in the course of this research. For further usability, the system would be modified to use derivatives of the CW equations for elliptical orbits [16] or even an orbit propagator.

The interceptor's position and velocity in relation to the target is continuously updated and fed into the CW equations. While in real applications this data would originate from on-board sensors, such as laser rangefinders or LIDARs, for the experimental system it is provided by the simulation environment. The prediction period can be preset in a configuration file. It was set to 1000 s for these experiments. The resulting trajectory is then plotted in three different displays (see Figure 2).

The 2D trajectory prediction depicts the trajectory in two planar views displayed alongside the attitude HUD. These views show the orbital plane edge-on from the side for the

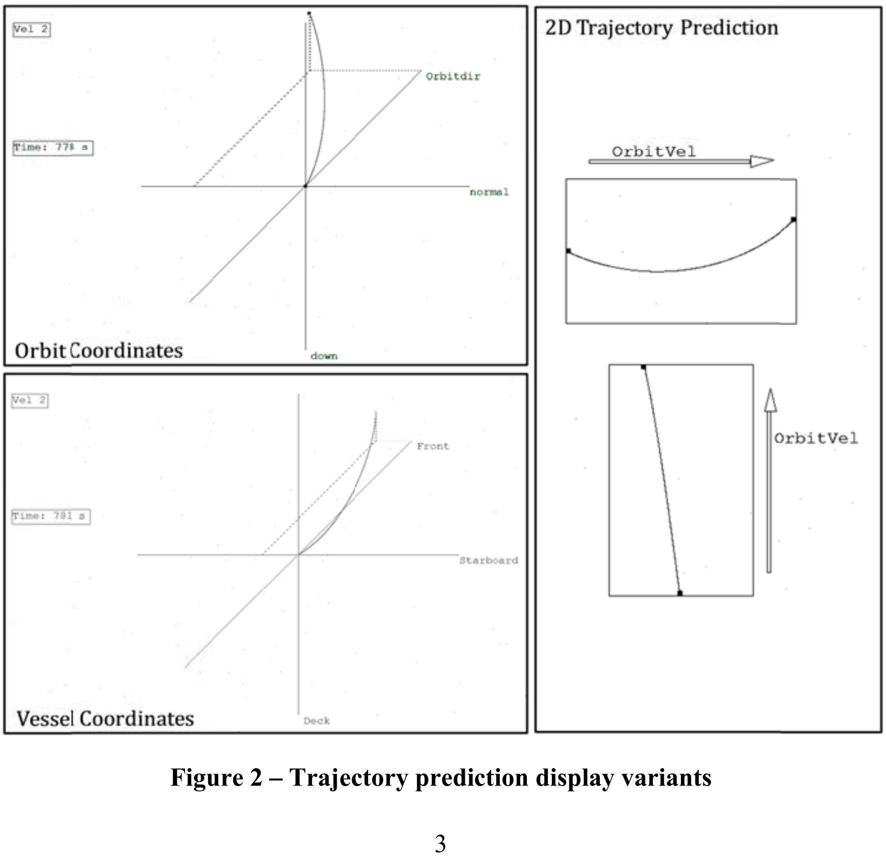


Figure 2 – Trajectory prediction display variants

out-of-plane motion, as well as from above for the in-plane trajectory.

The 3D displays show the trajectory prediction in a 3D projection in place of the attitude HUD. In the 3D orbit display the trajectory is shown in the fixed orbital reference system. This display does therefore not visualize interceptor spacecraft motion. The 3D vessel prediction display uses the body coordinate frame of the interceptor which is rotating with the spacecraft during attitude maneuvers. The position of the target object indicator, as well as the predicted trajectory, are therefore rotated around the ownship symbol as the interceptor attitude changes.

Simulation Environment

In order to keep the effort required to implement and test the HUD at a minimum, the *Orbiter* spaceflight simulator was used. *Orbiter* was developed at University College in London, UK for spaceflight simulation and education [17]. Although not open-source, it is available for free download and provides an application programming interface (API). Using this, users can add spacecraft and subsystems to the simulation environment and create mission scenarios. The proximity operations HUD was therefore implemented as a module for *Orbiter* and all experiments were also implemented in scenarios using this software (see Figure 3).

3. EXPERIMENT SETUP

Orbiter and the HUD module are run on a Windows 7 office desktop computer. The video is projected onto a 192 cm x 105 cm screen with 1280 x 720 pixels resolution. The test participants are seated with their eyes approx. 1.5 m in front of the screen. The computer is equipped with a Saitek Cyborg Evo Force joystick and a 3DConnexion SpaceExplorer for input devices.

Attitude and position data is extracted from *Orbiter* by another custom module which uses the functionality of the Data Distribution System (DDS) by RealTime Innovations (RTI). Using DDS, the data was published to a Simulink data-logging model. While this setup facilitates the transmission of the data via Ethernet and therefore data-logging on a remote computer, the data-logger was run in background on the simulation computer for these experiments.

The evaluation experiments were divided into three separate experiment series. Series I tested the general utility of an attitude HUD for space operations, as well as the differences in user performance in attitude maneuvering and estimation of relative positions generated by the inside-out and outside-in attitude representations. Series II tested the impact of the orbit and horizon reference systems on estimation of relative positions for approach maneuvers. The subject of series III was the usability of the trajectory prediction modes.

The participants for each series were recruited from the students and researchers at TU Munich's Institute of Astronautics (LRT). The reasoning behind this selection is that this group represents the pool from which operators of future telerobotic space systems will most likely be recruit-

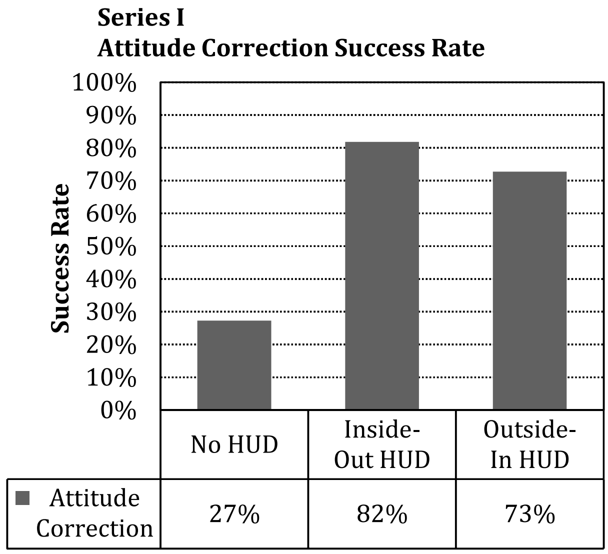
Figure 3 – Screenshot from Orbiter showing the outside-in HUD and multiple target objects for maneuvering experiments.

ed: aged 20-60, with technical education and above-average experience using computers and simulation systems. The participants were all male, aged between 25 and 57. Their average spaceflight simulation experience, subjectively rated between 1 (low) and 5 (high), was between 1.73 and 2.00 for the three series. Average flight simulation experience ranged between 2.10 and 2.91. The input device experience was only asked for in series I. Its average value was 3.00 for the joystick and 1.55 for the SpaceExplorer.

4. ATTITUDE HUD EVALUATION RESULTS

Experiment series I had 11 participants. Each of these had to complete three tasks: an attitude correction task, a series of attitude maneuvers and a series of relative position estimations. For each of these tasks success/failure, the time to complete the task, as well as the cumulative magnitude of the control input was logged. This magnitude is a representation of the intensity of the commanded thrust maneuvers, and thus propellant consumption. By multiplying the completion time and the control input magnitude a number indicating total expended impulse is computed. In addition to these objective measures, the participants also answered a number of questions. These concerned the participants' confidence about their orientation in space and the direction in which they had to steer, their ability to control the spacecraft rotation rates, as well as the required concentration for the control task. At completion of the experiment series, the participants were further asked which HUD they preferred in the attitude correction and maneuvering tasks, as well as the relative position estimation task.

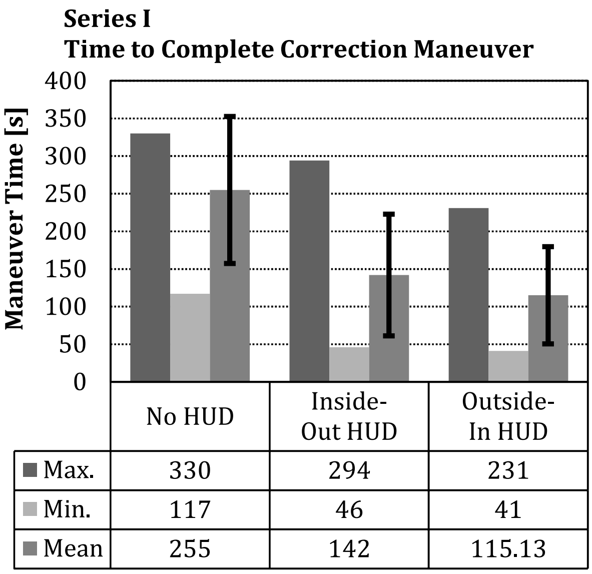
Prior to the actual experiment run, the participants individually completed approx. 20 minutes of training, during which they were introduced to the different HUD modes as well as the input devices and had to complete a number of maneuvers representative of the experiment tasks. At the end of the training, each participant had to select the input device he would use for the experiment. 73% opted for the joystick, 27% chose the SpaceExplorer. This distribution was expected, given the low familiarity the participants professed with the six-axis input device.



	No HUD	Inside-Out HUD	Outside-In HUD
Attitude Correction	27%	82%	73%

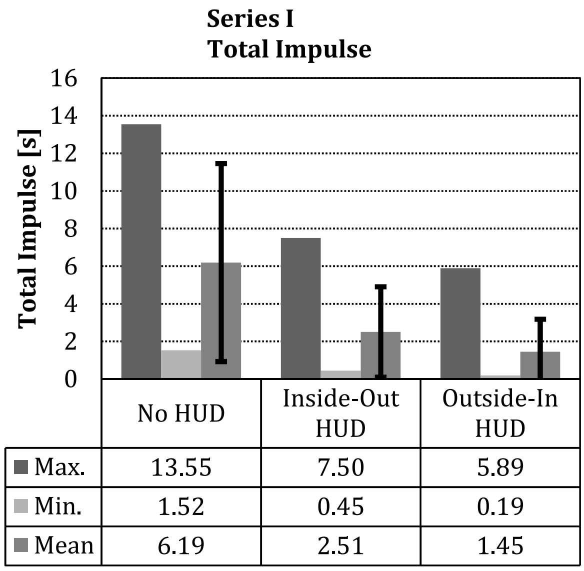
Figure 4 – Series I: Attitude correction success rate

In the attitude correction task, the spacecraft was initially in an arbitrary attitude with the Earth outside the field-of-view (FOV). The participants had to return the spacecraft to a 0° roll, 0° pitch, 0° yaw attitude in the horizon reference system. This means that it was to point in the direction of flight, with the x-y body plane parallel to the local horizon-



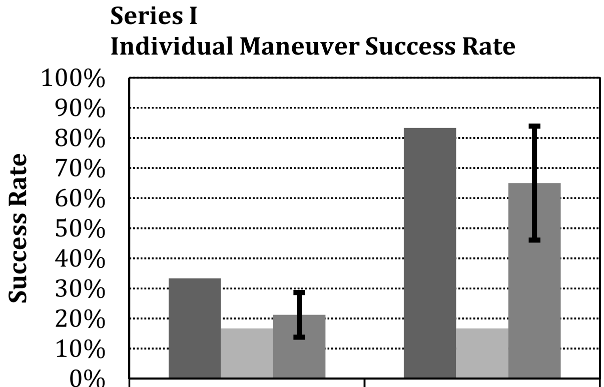
	No HUD	Inside-Out HUD	Outside-In HUD
Max.	330	294	231
Min.	117	46	41
Mean	255	142	115.13

Figure 5 – Series I: Measured completion times [s] for attitude correction maneuver



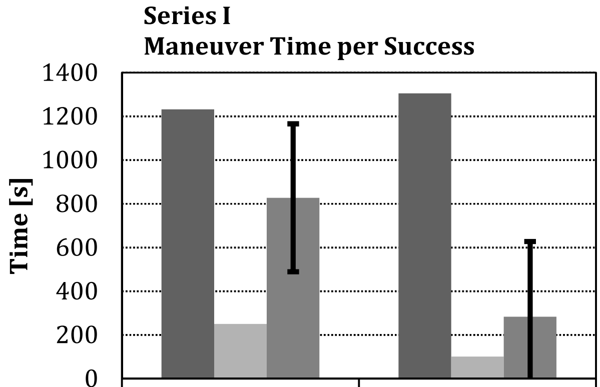
	No HUD	Inside-Out HUD	Outside-In HUD
Max.	13.55	7.50	5.89
Min.	1.52	0.45	0.19
Mean	6.19	2.51	1.45

Figure 6 – Series I: Total impulse [s] required for the attitude correction maneuver



	Inside-Out HUD	Outside-In HUD
Max.	33%	83%
Min.	17%	17%
Mean	21%	65%

Figure 7 – Series I: Attitude maneuver success rates



	Inside-Out HUD	Outside-In HUD
Max.	1232.00	1305.00
Min.	250.50	101.00
Mean	827.00	283.26

Figure 8 – Series I: Maneuver time [s] per successful attitude maneuver

tal plane. The tolerance bands were ±5° in pitch and yaw and ±2.5° in roll. The participants had to accomplish this task once without HUD assistance, then with each of the inside-out and outside-in HUDs.

Figure 4 shows the average success rates for the three situations. Without the HUD, only 27% of correction maneuvers were successful, whereas the use of the inside-out HUD or the outside-in HUD improved operator performance to 82% and 72%. This jump in performance is also evident for the average time to complete a successful maneuver (Figure 5), as well as the total impulse spent during a successful maneuver (Figure 6). The total impulse is here defined as the product of cumulative control input magnitude and time to complete, and is therefore given in seconds. Both the time and the impulse required for a successful attitude correction is substantially lower with an HUD than without it. This clearly shows the utility of an attitude HUD for teleoperated attitude maneuvering.

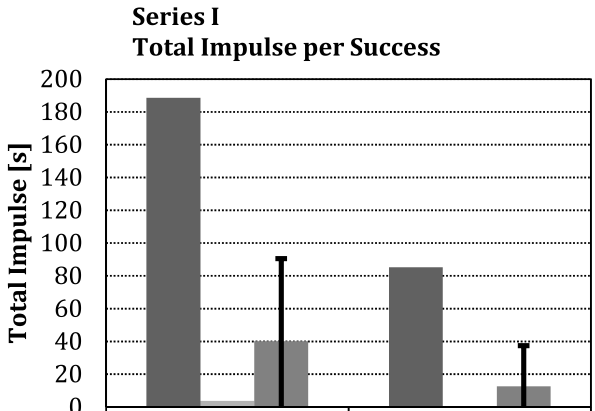
The data also indicates better operator performance with the outside-in HUD as compared to the inside-out HUD. This trend is weak and must therefore be confirmed in the second test of the series.

In the attitude maneuvering task, the participants had to achieve six different attitudes in series. A maneuver was considered successful if the operator managed to keep the spacecraft within ±5° of pitch/yaw and ±2.5° in roll angle of the commanded attitude for the duration of 5 s.

Of the data obtained by testing the 11 participants, one participant's data set had to be discarded for the outside-in test, since it was discovered after the experiment series that the Simulink data logger had experienced memory issues.

The mean success rate in the attitude maneuver series is given in Figure 7. Its average over all participants is 21% for the inside-out HUD and 65% for the outside-in HUD.

This indication of higher utility of the outside-in representation is reinforced by the statistics for maneuver time (see Figure 8) and total impulse (see Figure 9) per successful maneuver. These are determined by dividing the time and impulse spent by each participant for the complete maneuver series by the number of successful maneuvers. The mean time spent for each successful maneuver using the outside-in HUD is about 1/3 that for the inside-out HUD.



	Inside-Out HUD	Outside-In HUD
Max.	188.62	85.22
Min.	3.83	0.62
Mean	40.20	12.62

Figure 9 – Series I: Total impulse expense [s] per successful attitude maneuver

Using the outside-in HUD the participants furthermore used on average 31% of the impulse required with the inside-out HUD. It can therefore be stated that an outside-in attitude presentation enables the operator to show superior performance in attitude maneuvering compared to using an inside-out HUD.

The third experiment in series I addressed the question whether a difference exists between inside-out and outside-in displays for the task of judging a target's position in relation to the interceptor's body coordinate system as well as to the local orbital system. For this purpose, the participants were confronted by four scenarios in which a target object was within close range of the interceptor. The four cases were defined by whether or not the Earth was within the FOV, and by using the inside-out or outside-in HUD. Using the visual information only, the participants had to judge the target's relative position within the body-fixed and orbital coordinate frames and mark it qualitatively in the questionnaire.

With Earth in view, the inside-out HUD allowed the participants to correctly judge the target's position in the body-fixed coordinate system in 73% of the cases, compared to 45% using the outside-in system (compare Figure 10). The opposite performance is evident for the position in the local orbital coordinate system. The outside-in HUD intuitively depicts the interceptor's attitude within the orbital coordinate system. The participants thus find it easier to estimate the targets' relative positions within this system.

The overall low performance with the body-fixed coordinate system, as well as the difference between the HUDs however forms a surprise. The relative position in the body-fixed system can be discerned by looking at the simulator image and marking in what quadrant of the picture the target is situated. Apparently the HUD confused the participants so that 27% for the inside-out and 55% for the outside-in display were overwhelmed by this task.

Another cause for confusion within the body-fixed system seems to be the presence of Earth within the FOV. When Earth is not within view, the participants judge the target position correctly in 91% using the inside-out display, and 82% using the outside-in display (see Figure 11). This indicates better operator performance if the HUD is the only attitude reference available. However, without Earth as a natural reference, none of the participants was able to position the target within the orbital coordinate system using the inside-out HUD, while 36% were successful with the outside-in HUD.

Experiment series I therefore showed that an attitude HUD significantly increases operator performance during attitude maneuvers. Furthermore, an outside-in representation is superior in performance compared to an inside-out attitude display, in that it enables the operator to perform attitude maneuvers more successfully and efficiently. For estimating relative spacecraft positions, the outside-in display is of higher utility when the orbital coordinate system is used as a reference. Since this coordinate system is used for maneuver planning during proximity operations, this therefore shows that the outside-in HUD is the superior attitude representation for a proximity operations HUD. These results backed by the objective data are furthermore supported by the experiment questionnaire. At the end of the experiment series, the participants were asked which HUD they preferred in attitude correction/maneuvering and position estimation tasks, and which HUD was easier to use in each of these tasks (see Figure 12). For *attitude maneuvering*, the

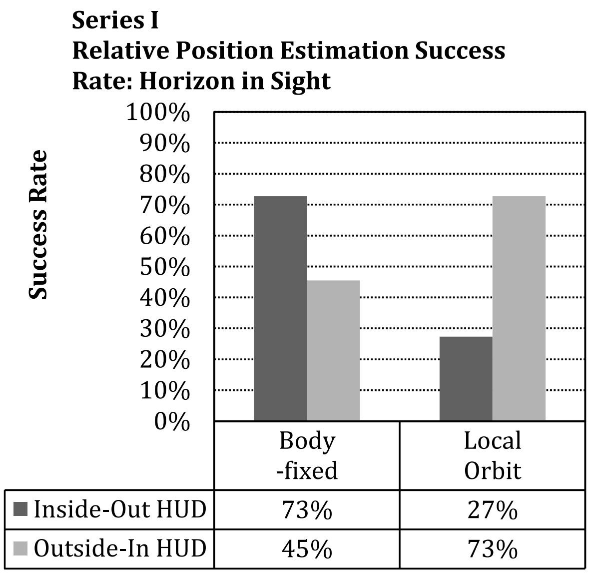


Figure 10 – Series I: Relative position estimation success rates with Earth horizon in FOV

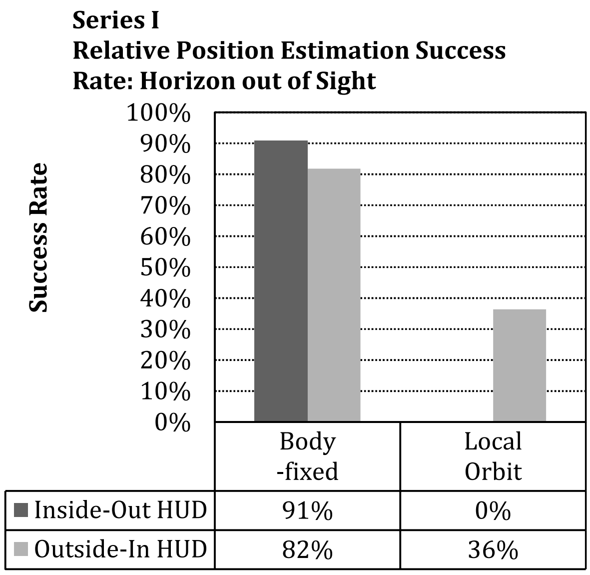
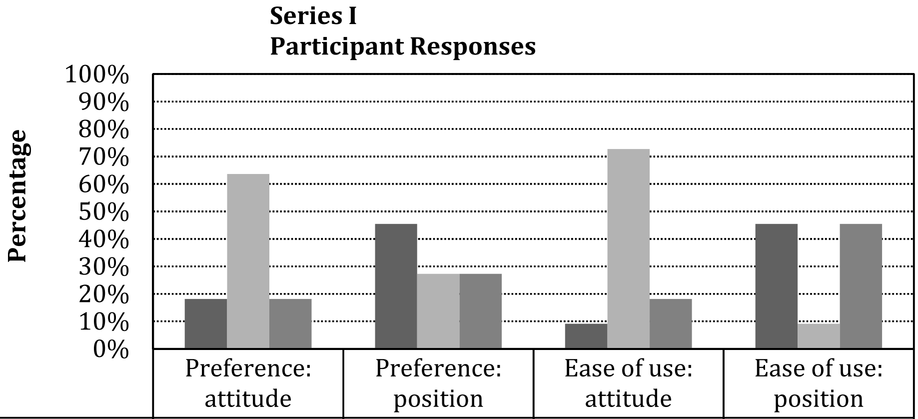


Figure 11 – Series I: Relative position estimation success rates with Earth horizon not in FOV



	Preference: attitude	Preference: position	Ease of use: attitude	Ease of use: position
Inside-Out HUD	18%	45%	9%	45%
Outside-In HUD	64%	27%	73%	9%
Indifferent	18%	27%	18%	45%

Figure 12 – Series I: Participant Responses concerning HUD preference and ease-of-use

outside-in HUD was strongly preferred and considered to be easier to use. For the *position estimation* tasks the inside-out display was preferred and considered easier to use. This reflects the data logged during the experiment. It must be noted that the ratio of indifferent responses is higher for the questions concerning the positioning tasks than for the attitude maneuvering tasks.

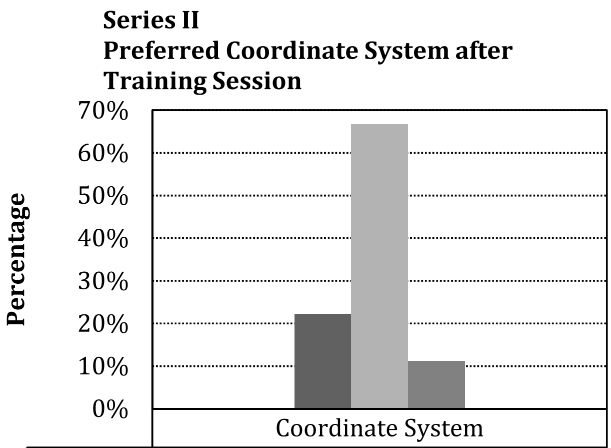
5. REFERENCE SYSTEM EVALUATION RESULTS

Experiment series II tested for the different effects the orbit and horizon reference systems have in the relative position estimation task. The 11 participants received about 15 minutes of training to familiarize themselves with the outside-in attitude HUD and the coordinate systems of the HUD. After training the participants answered the question which coordinate system they preferred (Figure 13).

The responses show a strong preference for the horizon reference system, which was expected, since with Earth in view, this reference system is the most intuitive of the three. The docking reference system was only used during the training session and was not part of the ensuing experiment run, since by its nature is not capable of assisting the operator in estimating positions relative to the orbital plane.

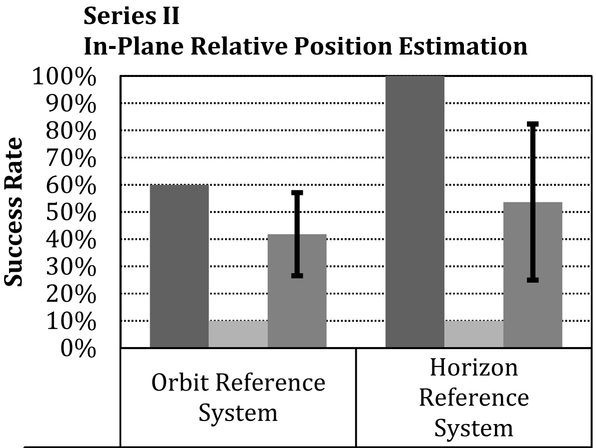
The participants were then shown a PowerPoint slideshow with 20 scenarios similar to the ones used in the third experiment of series I. In order to reduce experiment complexity, the attitude HUD used was exclusively the outside-in representation, reflecting the results of experiment series I. In ten scenarios the orbit reference system was used, in the further ten the horizon reference system. The participants had to qualitatively estimate the target's position in relation to the interceptor within the orbital plane (forward/aft, left/right), as well as in relation to the interceptor's local orbital plane (above/below or within the plane), and mark the positions on the questionnaire. Figures 14 – 16 show the statistics of these estimations separately for in-plane position component, out-of-plane position component, as well as the total position estimation. In order for the total position estimate to be correct, both the in-plane and out-of-plane components must be estimated correctly.

The in-plane results (Figure 14) show that an estimation success rate of 100% is achievable using the horizon reference system, whereas merely 60% were the maximum using the orbit reference system. The mean success rates are 42%



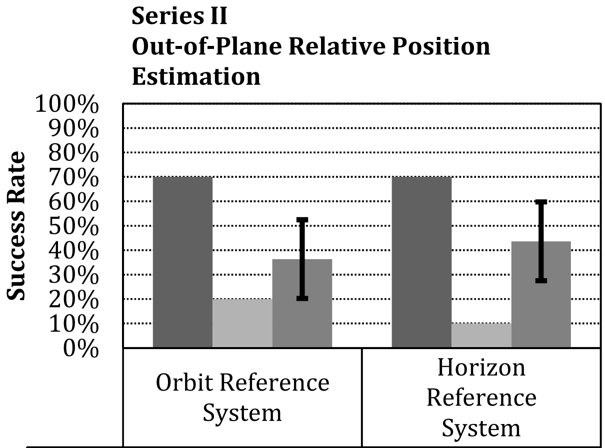
	Coordinate System
Orbit	22%
Horizon	67%
Docking	11%

Figure 13 – Series II: Reference coordinate systems preferences after the initial training session



	Orbit Reference System	Horizon Reference System
Max.	60%	100%
Min.	10%	10%
Mean	42%	54%

Figure 14 – Series II: In-plane relative position estimation success rate



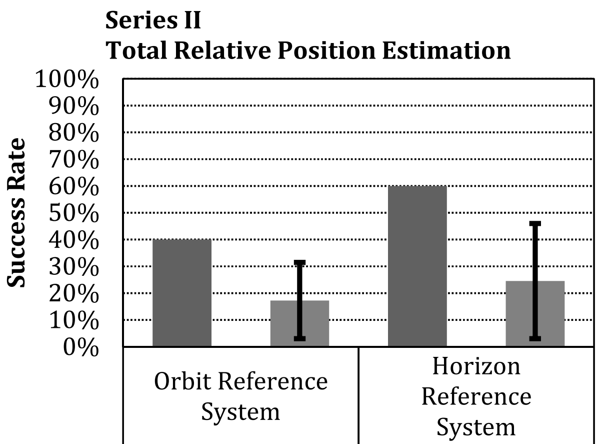
	Orbit Reference System	Horizon Reference System
Max.	70%	70%
Min.	20%	10%
Mean	36%	44%

Figure 15 – Series II: Out-of-plane relative position estimation success rate

for the orbit reference system, compared to 54% for the horizon reference system.

For the more difficult out-of-plane position estimation task (Figure 15), the maximum success rate in both reference systems was 70%. However, the mean success rate shows a slight superiority of the horizon reference system, with 44% as compared to 36% with the orbit reference system. This is surprising, since it was expected that estimating the out-of-plane component would be facilitated by the system using the actual orbital plane as the main reference. The fact that the horizon reference system corresponds with the natural attitude references available in the scenario seems to increase the participants' ability to orient themselves in space and thus also enhance their situation awareness.

This trend is also visible in the statistics for total estimation success (Figure 16). Using the horizon reference system, participants were more often able to correctly identify the relative position of the target, with a maximum of 60% and a mean of 25%. These low numbers also show the difficulty of the task and the need for other assistance systems beyond the attitude HUD for proximity operations maneuver planning.



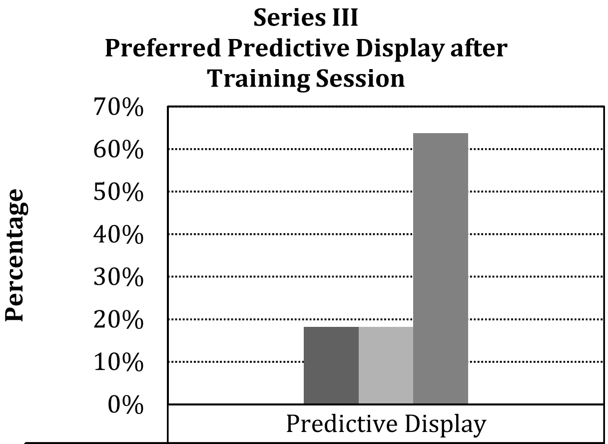
	Orbit Reference System	Horizon Reference System
Max.	40%	60%
Min.	0%	0%
Mean	17%	25%

Figure 16 – Series II: Total relative position estimation success rate

6. Trajectory Prediction HUD Evaluation Results

The third experiment series comprised the most complex task for the participants. The interceptor was placed at distances of 200 m and 500 m from a target (represented by a model of the Hubble Space Telescope). The participants had to approach the target, being supported by the 2D, 3D orbit and 3D vessel trajectory predictions. Each participant had to complete five approaches with each of the prediction displays. An approach was considered successful if the interceptor was stopped within a sphere with radius 20 m surrounding the center of mass of the target, with the rotation rates being reduced to zero. The relative velocity tolerance was ±0.05 m/s, the rotation rate tolerance ±0.0285°/s.

The test was run with 12 participants (the maneuver data of two of them was lost due to a malfunction of the Simulink logger and could not be recovered). The participants first individually trained using a single scenario, in order to get familiarized with the translation controls of the joystick, the



	Predictive Display
2D	18%
3D Orbit	18%
3D Vessel	64%

Figure 19 – Series III: Trajectory prediction display preferences after training session.

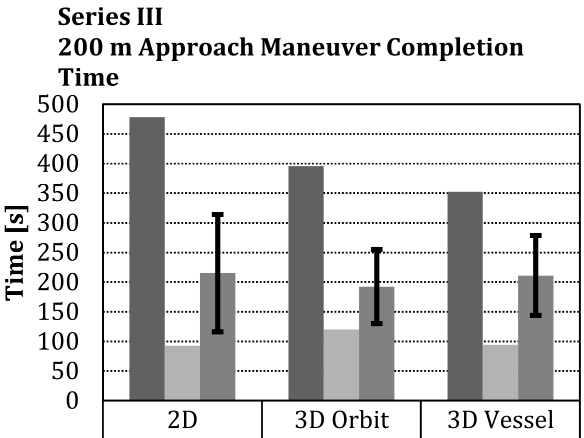
trajectory prediction displays, as well as the maneuvering task. At the end of the training session, the participants were asked their prediction display preferences (see Figure 19). 64% of the participants preferred the 3D vessel display over the others. This preference was expected since the 3D vessel display was considered by the authors to be the most intuitively accessible display.

During the actual experiment runs, the Simulink logging model again developed problems which were not noted until after the completion of the experiment series. This resulted in varying data sampling rates. In order to obtain comparable results, it was decided to discard all approaches during which the maximum time between samples was larger than 0.2 s, resulting in a minimum sampling rate of 5 Hz. For the 2D display, 11 out of 50 runs were thus discarded, for 3D orbit 14 of 50, for 3D vessel 11 of 50. The remaining maneuver data was furthermore separated according to the initial distance to target. The 200 m and 500 m runs were randomly distributed for each prediction display, resulting in a distribution of 200 m: 500 m cases of 27:12 for 2D, 23:13 for 3D orbit, and 19:20 for 3D vessel.

The first surprising result of the experiment series was that on the 200 m approach every participant was able to successfully complete every approach maneuver. On the 500 m approach there was one failure both using the 2D and 3D vessel prediction displays. Figure 17 and Figure 18 show the times required to complete the 200 m and 500 m approaches. The mean times are almost equal between the three display options, both for the short and the long initial distances.

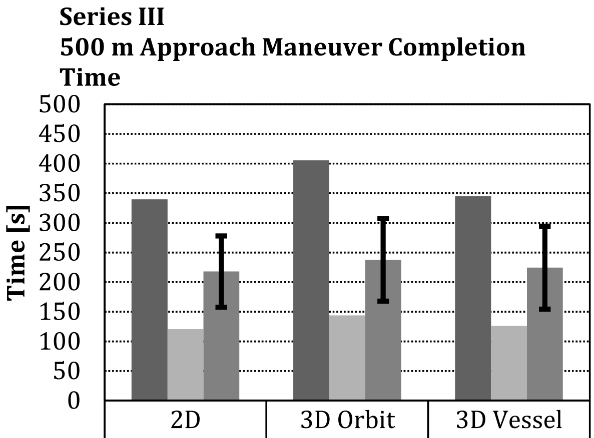
It is also interesting to note that it took the participants almost exactly as long to complete the 500 m approach as it did the 200 m. This is explained by the fact that the participants accelerated longer in the long-range scenarios, resulting in an average relative velocity of almost twice the value for the 500 m approaches.

The statistics of the total translation impulse expended during the approaches show a slightly worse performance for the 2D display at 200 m (Figure 20). Such an effect is not evident at 500 m initial distance, at which the total translation impulse for all three display versions is almost equal (Figure 21).



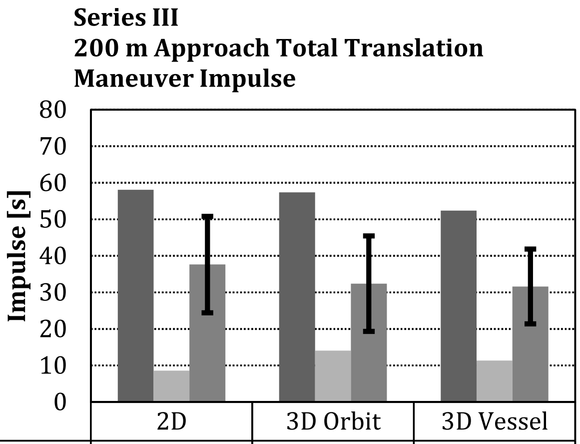
	2D	3D Orbit	3D Vessel
Max.	478.19	395.35	352.51
Min.	92.69	120.22	94.27
Mean	214.97	192.59	211.12

Figure 17 - Series III: Time [s] to complete 200 m approach



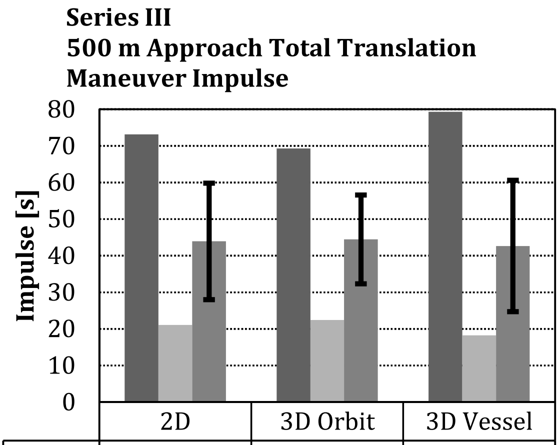
	2D	3D Orbit	3D Vessel
Max.	339.56	405.45	345.11
Min.	120.52	143.98	126.16
Mean	217.88	237.49	224.33

Figure 18 - Series III: Time [s] to complete 500 m approach



	2D	3D Orbit	3D Vessel
Max.	58.08	57.37	52.39
Min.	8.59	14.06	11.33
Mean	37.61	32.39	31.63

Figure 20 - Series III: Total translation impulse expense [s] on 200 m approach

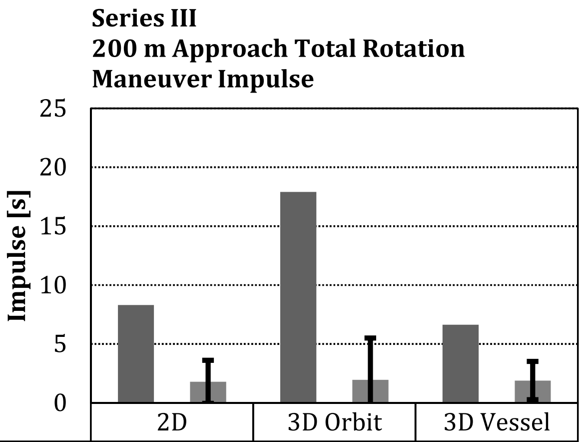


	2D	3D Orbit	3D Vessel
Max.	73.12	69.32	79.30
Min.	21.11	22.45	18.25
Mean	43.92	44.47	42.66

Figure 21 - Series III: Total translation impulse expense [s] on 500 m approach

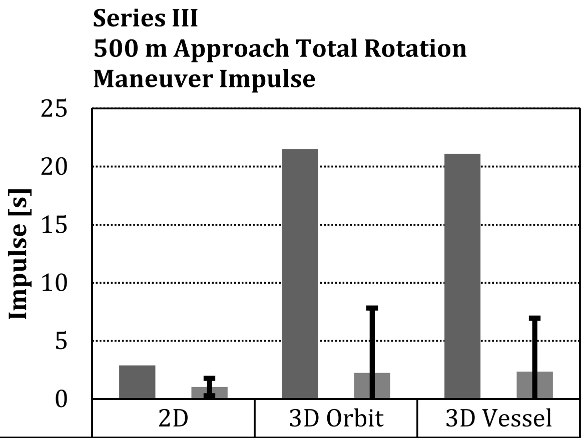
The measured data for total impulse for rotation maneuvers (Figure 22 and Figure 23), as well as relative velocity at the 20 m mark (Figure 24 and Figure 25), which is an indicator for the required braking thrust and thus the severity of plume impingement, is just as inconclusive.

It is therefore concluded that there exists no difference in operator performance due to the trajectory prediction display version. However, the participants voiced strong preferences after the training session. It is interesting to note that these preferences changed after the experiment runs (see Figure 26). The 3D vessel display was still preferred over the 3D orbit display, but came in second after the 2D system. This difference is not justified by the maneuver data. Participants stated that the advantages of the 2D display were its clear presentation and the fact that the attitude HUD was in view alongside it. The 3D displays had the general disadvantage of being more difficult to understand due to the 3D content being projected onto the 2D plane and due to the low resolution of the *Orbiter* drawing functions. With the 3D orbit display it was not possible to discern the spacecraft attitude rates. These were however



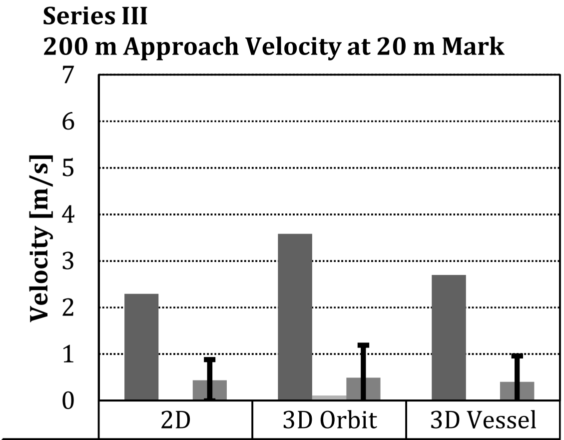
	2D	3D Orbit	3D Vessel
Max.	8.31	17.91	6.64
Min.	0.00	0.00	0.00
Mean	1.78	1.96	1.89

Figure 22 - Series III: Total rotation impulse expense [s] on 200 m approach



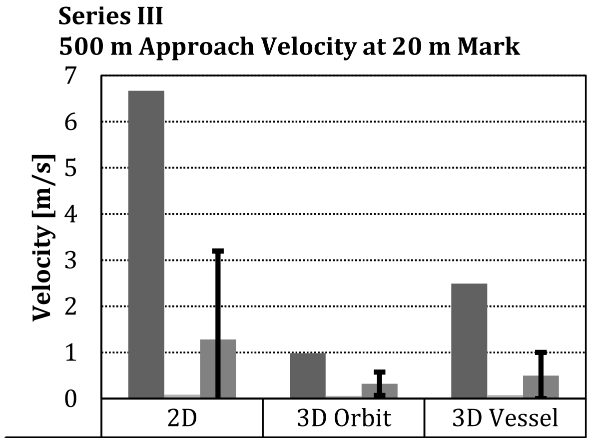
	2D	3D Orbit	3D Vessel
Max.	2.88	21.52	21.11
Min.	0.00	0.00	0.00
Mean	1.03	2.24	2.35

Figure 23 - Series III: Total rotation impulse expense [s] on 500 m approach



	2D	3D Orbit	3D Vessel
Max.	2.29	3.59	2.70
Min.	0.00	0.11	0.00
Mean	0.44	0.49	0.40

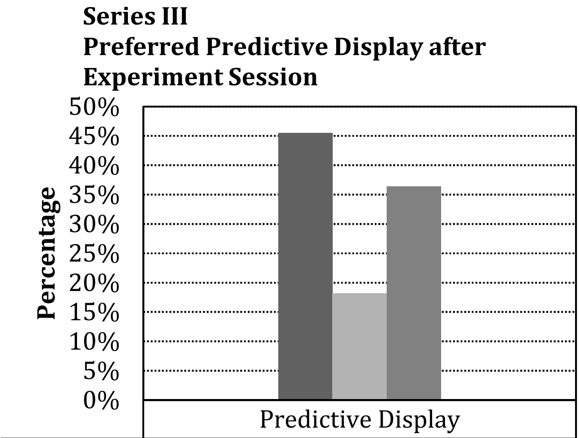
Figure 24 – Series III: Approach velocity [m/s] at 20 m mark on 200 m approach



	2D	3D Orbit	3D Vessel
Max.	6.67	0.98	2.49
Min.	0.09	0.06	0.08
Mean	1.28	0.32	0.50

Figure 25 – Series III: Approach velocity [m/s] at 20 m mark on 500 m approach

visible in the 3D vessel display. A problem the 2D and 3D displays shared was missing scale indicators with which to measure distances.



	Predictive Display
2D	45%
3D Orbit	18%
3D Vessel	36%

Figure 26 – Series III: Trajectory prediction display preferences after experiment runs

Based on these comments it was decided to further refine the 3D vessel display before integrating it into the Third Eye user interface.

7. Adaptations to the Third Eye User Interface

The Third Eye situation awareness enhancement system is designed to improve the operator's awareness of his surroundings and the relative situation between interceptor and target during proximity operations. For this purpose, it uses a robotic camera arm mounted on the interceptor to provide adaptive vantage points of the space between the spacecraft. The video streams from the camera arm and from a bus-fixed camera are displayed in a graphical operator interface, along with a 3D representation of the posture of the camera arm, an attitude HUD and a trajectory prediction. Refer to [11] for a more detailed overview of the Third Eye system.

Due to the results of this study, the Third Eye HUD system will use an outside-in attitude HUD referenced to the local orbital plane. Although the horizon reference system proved superior in the experiments, the orbit system was chosen for the reason that the hardware-in-the-loop simulation environment at LRT only supports in-plane movement. The features added to the attitude HUD due to participant comments during the experiment runs are: pitch and yaw rate indicator strips and numerical displays; a roll angle scale, roll rate indicator strip and numerical display; as well as a numerical display for target relative velocity. Since in teleoperation via a single data relay satellite the operator will have to cope with about 0.53 s signal roundtrip time delay, the attitude angle and rate indicators are provided twice. Once in green, showing the commanded attitude and rates based on the operator input. Once in red, showing the actual angles and rates as received in spacecraft telemetry. The operator uses the commanded display for actual guidance, while the feedback display is used as a reference.

The trajectory prediction display is provided in a separate window to the left of the camera views. The 3D vessel system is implemented with some changes compared to the experimental version in *Orbiter*. The 3D axes are no longer projected onto the 2D plane but actually drawn in 3D using OpenGL drawing functions. The display scale is adapted with the target distance in order to fully use the available space. The horizontal and vertical planes are visible in light gray, with the scale indicated on the rim. The target symbol size is changed with the distance to target. The target and the predicted trajectory are provided twice, to account for the signal time delay. As with the attitude HUD, the commanded trajectory and predicted target position are drawn in green, the actual position in red.

This Third Eye HUD is used in the docking experiments evaluating the Third Eye system and the feasibility of teleoperated docking to an uncooperative target.

8. CONCLUSIONS

The user studies conducted for this paper show that the availability of an attitude HUD greatly facilitates teleoperated attitude maneuvering in an orbital environment. An outside-in attitude representation is furthermore superior to an inside-out display in supporting operator attitude maneuvering performance.

This result is in agreement with findings for the comparison of inside-out and outside-in display for Unmanned Underwater Vehicles (UUVs) [14]. In that study it was concluded that outside-in displays reduce the need for operators to mentally integrate information in order to gain understanding of the vehicle state, since it already displays pre-integrated information. Furthermore, all symbols in the outside-in display move in the direction of the command input, whereas the roll and pitch indicators in the inside-out HUD rotate in the opposite direction. The outside-in HUD is therefore more intuitive to the operator's mental model. This results in a reduced likelihood of control-reversal errors, and thus in increased maneuver guidance efficiency and safety. These effects were reproduced in our study for an application in space teleoperation.

The results presented in this paper have also shown the outside-in display to be the superior HUD for estimating target relative positions within the orbital plane, which is important for long-range approach maneuvers. At short ranges, when the target position in the interceptor body coordinate system is more relevant, the inside-out display is the better option. For such position estimation tasks a coordinate reference system based on the local horizontal plane is indicated to be preferred over an orbital plane reference system. This could be due to the agreement between artificial and natural attitude cues for the horizon reference system. However, the differences in operator performance measured during these experiments are too small for a definitive statement. More research in this field is therefore needed.

The trajectory prediction display variants designed for supporting approach maneuvers generate no differences in operator performance when compared against each other. However, operator perception accredits the 2D and 3D vessel displays with higher usability than the 3D orbit display. The 3D vessel display is therefore to be further detailed and refined in the future.

9. SUMMARY

This paper provided a brief overview of the experimental proximity operations HUD developed at LRT. It then proceeded to describe the evaluation experiments conducted to determine which HUD configuration is most beneficial for operator performance. The results of these experiments are discussed and some conclusions are drawn for future development and research work. Furthermore, the adaptations of the HUD made when incorporating it into the Third Eye situation awareness enhancement operator interface are detailed.

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BIOGRAPHIES

Markus Wilde *is a research assistant at the Institute of Astronautics (LRT) at Technical University Munich, Germany. He is a graduate of this university where he acquired his Master of Science in Aerospace Engineering in 2008. His research focus is teleoperated rendezvous & docking for future On-Orbit Servicing and space debris removal missions. He pursues his Ph.D. in aerospace engineering by developing and evaluating the Third Eye situation awareness enhancement system and its effects of operator performance.*

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