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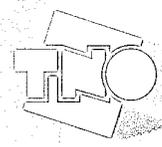
TNO Human Factors  
Research Institute

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**Operator performance in multi  
Maritime Unmanned Air Vehicle  
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TNO Human Factors  
Research Institute

Kampweg 5  
P.O. Box 23  
3769 ZG Soesterberg  
The Netherlands

Phone +31 346 35 62 11  
Fax +31 346 35 39 77

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**Operator performance in multi  
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author  
L. van Breda

date  
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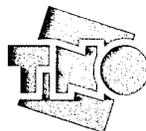
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<b>11. AUTHOR(S)</b> L. van Breda		
<b>12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> TNO Human Factors Research Institute Kampweg 5 3769 DE SOESTERBERG		
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In opdracht van de Koninklijke Marine werd een verkennende studie uitgevoerd naar de mens-machine interface voor het besturen van "Maritime Unmanned Air Vehicles" (MUAV's). Dit rapport beschrijft een simulatorexperiment waarin werd nagegaan hoe effectief operators onder verschillende verbaal/cognitieve werklast condities een bewegend doel kunnen volgen tijdens een multi-MUAV supervisietaak.

De experimentele resultaten laten zien dat verhoogde werklast geen invloed had op de mate waarin het doel in beeld werd gehouden. Dit was gemiddeld ongeveer 100% bij bijwerkfrequenties van het sensorbeeld van meer dan 4 Hz, en daalde naar ongeveer 60% bij een bijwerkfrequentie van 1 Hz. Aangezien de proefpersonen de opdracht kregen om primair aandacht te besteden aan de verbaal/cognitieve taak, kon deze verhoogde aandacht evenwel niet worden gegeven, vooral niet bij hoge werklast. Dit leidde tot vergroting van de volgfout.

Mede op basis van eerder onderzoek (Van Breda & Passenier, 1993) wordt geconcludeerd dat een hoge bijwerkfrequentie van het sensorbeeld essentieel is voor het nauwkeurig besturen van MUAV's. Hoewel er momenteel veel tijd wordt gestoken in het opvoeren van de transmissie bandbreedte van de downlink zijn er slechts beperkte vorderingen (Schwartz e.a., 1992; NATO, 1993; Rochus & Garcia, 1995; Van Breda, 1995). Vandaar dat wordt aanbevolen in een vervolgstudie na te gaan hoe prestatie en oriëntatie van de operator kunnen worden verbeterd bij lage bijwerkfrequenties, zodat de bandbreedte van de downlink voor wat betreft de besturing van MUAV's minder van belang is. Dit kan onder andere door integratie van synthetische informatie over MUAV status en oriëntatie in het sensorbeeld ("synthetic image augmentation"). Kunstmatige voertuigreferenties, bijvoorbeeld, of een synthetisch perspectivisch landschap, gegenereerd vanuit de actuele MUAV-positie en getoond met een hoge bijwerkfrequentie (60 Hz), kunnen het oriëntatie- en anticipatievermogen verbeteren.

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#### SUMMARY

Under contract by the Royal Netherlands Navy, an exploratory study was conducted concerning the man-machine interface and task characteristics for controlling Maritime Unmanned Air Vehicles (MUAVs). This report describes a simulator experiment investigating how effective operators can track a moving target in a multi MUAV supervisory control task, under different verbal/cognitive workload conditions.

Results of the experiment show that moderate and even high workload conditions did not affect the mean target coverage of the sensor image. This was about 100% at image update frequencies of 4 Hz and more, decreasing to about 60% at 1 Hz update frequency. This may be explained by the fact that, in the latter case, the tracking task became more discontinuous, which demanded more attention for anticipation. Since the subjects were instructed to give primary attention to the verbal/cognitive task, this extra attention was not fully available, in particular not during high workload conditions. This resulted in an increase of the mean viewing (tracking) error. It is suggested to focus further research on ways to improve operator performance and awareness at low image update rates, for instance by integrating synthetic information on orientation and MUAV status into the sensor image ("synthetic image augmentation").

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**Taakprestatie bij multi "MARITIME UNMANNED AIR VEHICLE" besturing**

L. van Breda

**SAMENVATTING**

In opdracht van de Koninklijke Marine werd een verkennende studie uitgevoerd naar de mens-machine interface voor het besturen van "Maritime Unmanned Air Vehicles" (MUAV's). Dit rapport beschrijft een simulatorexperiment waarin werd nagegaan hoe effectief operators onder verschillende verbaal/cognitieve werklast condities een bewegend doel kunnen volgen tijdens een multi-MUAV supervisietaak.

De experimentele resultaten laten zien dat verhoogde werklast geen invloed had op de mate waarin het doel in beeld werd gehouden. Dit was gemiddeld ongeveer 100% bij bijwerkfrequenties van het sensorbeeld van meer dan 4 Hz, en daalde naar ongeveer 60% bij een bijwerkfrequentie van 1 Hz. Dit kan worden verklaard doordat in de laatstgenoemde geval de volgtaak discontinu werd, waardoor anticipatie werd bemoeilijkt en meer aandacht vergde. Aangezien de proefpersonen de opdracht kregen om primair aandacht ter besteden aan de verbaal/cognitieve taak, kon deze verhoogde aandacht evenwel niet worden gegeven, vooral niet bij hoge werklast. Dit leidde tot vergroting van de volgfout. Aanbevolen wordt in een vervolgstudie na te gaan hoe prestatie en oriëntatie van de operator kunnen worden verbeterd bij lage bijwerkfrequenties, bijvoorbeeld door integratie in het sensorbeeld van synthetische informatie over MUAV status en oriëntatie ("synthetic image augmentation").

## 1 INTRODUCTION

### 1.1 Background

Maritime Unmanned Air Vehicles (MUAVs) are airframes with a payload that are launched and propelled through the air without an operator on board. Instead, these vehicles are remotely controlled by an operator who is situated in a base control station. The Royal Netherlands Navy (RNLN), as well as other participating countries in NATO Naval Armament Group (PG/35), are interested in the development of these air vehicles, in particular for anti-surface-warfare purposes (NATO staff requirement, 1992). This includes surface reconnaissance, surveillance and target acquisition (RSTA), as well as battle damage assessment (BDA). As MUAVs are not strictly autonomous, operators are closely involved, guiding the vehicles towards their targets while interpreting threat, tactical, and sensor information. Especially when tracking targets, the operator has to ensure that he is accurately following the target while envisioning an environment which is remotely obtained. As the sensor image has a limited resolution and field of view (FOV), and no vestibular feedback of the air vehicle behaviour is obtained, it is obvious that operator behaviour is crucial for effective MUAV operation. Therefore, the TNO Human Factors Research Institute was asked to investigate the human-machine parameters of the MUAV user interface that affect operator performance.

In a first approach, a literature review (Eisen & Passenier, 1991a) was performed, based on NATO launch, mission and recovery requirements (LaMonica, 1988; NATO, 1990, 1992; Schwartz et al., 1992). It was concluded that the human-machine interface should be optimally designed for supervisory control (target acquisition phase) and tracking for RSTA/BDA. NATO staff targets (NATO, 1990) indicate that MUAVs should only be used under certain predetermined conditions. For instance, a certain predetermined observation distance to the target should be maintained in order to avoid early detection of the MUAV. Since target loss must be limited to a minimum, it is important to select the proper technology for the MUAV and carefully design the MUAV user interface. Eisen and Passenier (1991b) also concluded that MUAV operators are involved in several functions during MUAV missions. Guidelines for information presentation were specified, such as sensor, tactical, and strategic information.

In a next phase, an exploratory experiment was conducted (Van Breda & Passenier, 1993) in which an operator had to control a MUAV and maintain a predetermined constant observation distance relative to a fast moving target. Doing so, the operator was confronted with multiple degrees of control such as altitude, horizontal position and yaw of the MUAV as well as pitch, yaw and FOV of the sensor system, each of these affecting the size and position of the sensor footprint. Results of the experiment indicated that accurate tracking is only possible when a control input device is used based on a coupled control algorithm. Only then, the 4 Hz sensor image update frequency, as recommended by Vitro (Schwartz et al., 1992), will lead to an acceptable tracking performance by the operator. Update frequencies less than 4 Hz will cause target loss.

The study only investigated tracking performance with single MUAV operation. However, the RNLN considers effective over-the-horizon MUAV systems important for heli operation

support (Fortgens, 1994), in particular configured in so called multi-MUAV clusters. Multi-MUAV missions are partly pre-programmed, partly manually controlled. For example: one MUAV for tracking targets or for RSTA/BDA, two MUAVs as relay stations (the first is moving to the target area to take over the tracking job as soon as the actual tracking MUAV has to return to base for refuelling; the second is moving from the target area back to base to get refuelled), and one MUAV is being refuelled at the base. The operator is involved in a supervisory control task: supervision of tracking, tactical, strategic and MUAV status information, and simultaneously tracking targets manually. Since operator workload may play an important role under these operational circumstances, an experiment was conducted to determine the extent to which tracking performance is affected by the supervisory tasks. This report describes this experiment and the results.

During multi-MUAV missions, only the tracking MUAV is under direct control by an operator, whereas the other air vehicles are more or less autonomously flying from waypoint to waypoint, or waiting and hovering at predetermined positions, until action is needed. A global function description of a multi-MUAV mission contains the following main functions:

- *Track targets*

Once the targeting MUAV is at a predetermined observation (stand-off) distance, the operator uses the control input devices and visual feedback to minimize the deviation between the crosshair of the sensor image and the moving target. It should be noticed that a MUAV is a relatively fast responding system which has severe restrictions in minimum observation distance (forward distance to the target to be maintained) and field of view (FOV) of the sensor. Information concerning the target's future position may be derived from the perceived target position and orientation (perceptual anticipation) and from knowledge of the MUAV and target movement (cognitive anticipation). Since the primary mission of the MUAV system in the present study is probably RSTA, the a-priori information on target characteristics is minimal. Therefore, with regard to target tracking, cognitive anticipation is hardly supported.

- *Supervise*

The MUAV operator has to supervise a multiple MUAV system, monitoring tactical mission information and control/status information to judge the state of the air vehicles. Therefore, the mission scenario should be considered as a procedure, supervised by the operator. He verifies the different system parameters and take the necessary corrective actions.

- *Communicate*

The MUAV operator communicates with the Command. It is suggested that the operator has an open connection through the communication network using a headset, scanning messages that are assigned to him. It is essential that the operator recognizes these messages correctly and acts accordingly.

The RNLN is interested to know whether a single MUAV operator is able to perform multiple tasks in order to fulfil the functions described above. It seems logical to think that tasks, being performed simultaneously, affect each other (e.g. calculating and discussing).

But it is also known that task combinations exist that can very well be performed in parallel (e.g. steering a car and discussing with someone, or listening to the radio). Therefore, multiple task performance should be investigated before a new system is developed. A model that can be used to evaluate human interface principles and to predict workload, is the multiple resource model developed by Wickens (1984). This model is specific for multiple (continuous) task performance and distinguishes three resources (see also Veltman & Gaillard, 1991):

- modalities; channels through which information is obtained (e.g. visual, verbal), or the way response is generated (e.g. verbal, manual);
- stages of information processing; perceive, central processing, respond;
- coding; the way information is being processed. This can be spatial (e.g. orientational tasks) or verbal (e.g. retaining names).

The model predicts that, when (independent) parallel tasks use the same resource (interfere), the task performance on each individual task will decrease. This will not happen when parallel tasks use different resources. For instance, verbal tasks can easily be combined with visual tasks; a task in an early phase of information processing (e.g. perceive, pattern recognition) can easily be combined with a task that generates a response (e.g. steering); a task that processes spatial information (e.g. interpreting radar information) can easily be combined with a verbal task (e.g. communicate).

## 1.2 The experiment

In order to determine the effect of verbal/cognitive workload on tracking performance, an experiment was conducted. Subjects had to approach a moving target in an open sea scenario and follow this target at a predetermined stand-off distance. In the experiment, a coupled control input device (Van Breda, 1993) was used, in which one single joystick controlled footprint and air vehicle (Eisen & Passenier, 1991b). The control signal was interpreted by a control algorithm for maintaining a fixed stand-off distance (2000 m). If the target distance varied, the sensor footprint could be manually controlled in forward or backward direction by pushing or pulling the joystick. The corresponding air vehicle motions were calculated and executed. By moving the joystick sideward, the horizontal viewing angle was controlled by the yaw rate of the MUAV air vehicle.

To vary workload, a verbal/cognitive task had to be performed in addition to this visual-manual-spatial tracking task. This so called continuous memory task (CMT) (Boer, 1992; Veltman & Gaillard, 1993) was presented to the subjects by means of a verbal display (headset) and was characterized by detecting certain target letters and mentally counting the frequency of their appearance. The task difficulty was varied by the number of target letters. The subjects were asked to perform the tracking task as accurately as possible, but to give the CMT the highest priority.

It should be noticed that the CMT only globally reflects the future MUAV operator task aspects while fulfilling the functions as described in § 1.1. It is obvious that specific visual or manual tasks (for instance emergency diagnosis and control tasks during erroneous MUAV functioning) could affect the operator task performance differently. This experiment

is considered as a first test, so a normative approach was taken: the operator will not make procedural errors and no vehicle malfunctioning will occur.

According to a former experiment (Van Breda & Passenier, 1993), the sensor image update frequency is one of the crucial factors to affect operator tracking performance. Therefore, both image update and CMT workload were varied in the experiment. With respect to the factor 'image update frequency', the sensor video image was supposed to be obtained through a digital datalink, resulting in image update frequencies varying from 1 to 10 Hz. For the factor 'cognitive workload', the difficulty of the CMT was varied at three levels: 'low', 'moderate' and 'high'.

In summary, the MUAV operator has to minimize deviations between the crosshair of the sensor image and the moving target. Based on the former experiment, it can be expected that low sensor image update frequencies will deteriorate perceptual anticipation, causing relatively large viewing errors, and therefore decrease the operator tracking performance.

Wickens' multiple resource model predicts that the (visual/manual) spatial tracking task can well be combined with a verbal/cognitive task. Therefore, with regard to the verbal/cognitive workload introduced by the CMT, it can be expected that high workload will hardly affect the tracking task performance.

## 2 METHOD

### 2.1 Subjects

Ten male subjects participated in the experiment. These subjects were starting College students. Their age varied from 21 to 39 years (average 25.6 years).

### 2.2 Task

Each subject was sitting at a desk, providing a display and joystick for tracking targets, and a display and headset for the additional CMT. During each trial, the subjects initially flew a MUAV at 5000 m distance from a fast moving target ship. This target ship had to be approached until 2000 m stand-off distance. During this approach, the sensor remained zoomed out (46.7° FOV). Once the desired stand-off distance was obtained, the subject had to zoom in on the target ship (3° FOV) and track the target ship, which means to keep the crosshairs of the sensor image as accurately as possible on a special marker at the stern of the target ship (tracking phase). However, this target ship performed unexpected course changes. In case of target loss, it was allowed to zoom out and retrace the target ship.

At a certain moment, an additional task had to be performed. If so, a set of (two or four) target letters would appear on a screen and a button for acceptance had to be pushed, to start the CMT. A series of 40 letters were presented in the subject's headset: one letter every 1.5 s. The subject had to press a 'recognition' button once, each time he recognized one of

the target letters. Moreover, he had to push the 'recognition' button twice, each time any target letter was recognised for the third time. In case a double response was expected, the subject heard 'Correct' when giving a double response; the subject heard 'Wrong' once an omission was made or when the subject responded at the wrong moment. After the response (either 'Correct' or 'Wrong') the tally for the letter that was presented, was reset to zero. A CMT with two target letters was considered to be of 'moderate workload', a CMT with four target letters of 'high workload' (see also Aasman, Mulder & Mulder, 1987; Veltman, 1991).

The subject was instructed to track the target ship as accurate as possible, using the coupled control system. Although, the additional verbal/cognitive task had to be considered as the highest priority task.

Each trial was finished after four minutes of tracking. Then, the next trial would start.

### 2.3 Experimental design

The values of the independent variables were varied as follows:

- |   |                       |
|---|-----------------------|
| 1 Image update frequency (3 levels):    | 1 Hz, 4 Hz and 10 Hz. |
| 2 Verbal/cognitive workload (3 levels): | low, moderate, high.  |

These variables were independently combined within subjects in a balanced order. This made up to a total of 9 conditions.

### 2.4 Instrumentation

The experiment was carried out on the MUAV simulator developed at the TNO Human Factors Research Institute. This simulator was based on a Silicon Graphics Iris 4D workstation for calculation of the position of the footprint and for generation and presentation of the tactical and sensor information. The subject was seated in a cubicle in which a monitor and control devices were installed. Control actions of the subject were fed into the Iris in which a mathematical model of the target ship behaviour and of the MUAV including sensor characteristics were implemented. A right-hand joystick was used for combined control of sensor and MUAV motion in the so-called coupled control mode (Van Breda & Passenier, 1993).

For generation and presentation of the CMT task, a Taskomat was used (Spoelstra, 1993), consisting of a IBM PC with timer response and speech interface for stimulus generation and verbal presentation.

Detailed information on simulator characteristics, MUAV and target behaviour are presented in the Appendix.

## 2.5 Procedure

The subjects came in pairs during one day. First, they were introduced to the MUAV simulator by the instructor, who explained the control input devices and the presented information on the screen. Then, a training session took place in which three tracking test-trials (update frequency of 10, 4, 1 Hz respectively) had to be performed. Finally, the subjects were trained to perform the CMT (moderate, high workload respectively), separately from, and simultaneously with the tracking task. The task performance was verified by the instructor.

During the actual experiment, each subject had to perform 6 blocks of 3 trials each. When one subject was performing, the other was waiting and took over after each block. The instructor closely monitored the subject's task performance. In particular the CMT performance had to be monitored and kept at a maximum level.

## 2.6 Dependent variables and analysis

The sample rate for collecting data of the state variables was 4 Hz. For the analysis the following dependent variables were calculated, representing the operator performance:

- 1 *target coverage*: percentage of time during which the target ship's stern marking was visible on the screen;
- 2 *viewing error*: the total angular difference between the crosshair of the sensor image and the marking on the target ship, expressed in degrees.
- 3 *CMT score*: percentage correct response of target-letter hits and of count 3 target-letter hits.

The analysis concerned the root mean square error (RMS error) of these variables, starting at the moment that the MUAV was within 3000 m observation distance. On these data, an analysis of variance (ANOVA; Winer et al., 1991) was performed.

## 3 RESULTS

### 3.1 Target coverage

Fig. 1 shows the target coverage, for the three image update and workload conditions, averaged over the subjects.

As can be seen in Fig. 1, the target coverage was decreasing with lower image update frequencies. This was nearly 100% at 10 Hz, and 95% or more at 4 Hz, but only about 60% at 1 Hz. According to a 3 (Update frequency)  $\times$  3 (Workload) ANOVA this effect was significant [ $F(2,18)=15.09$ ;  $p < <0,01$ ]. However, the ANOVA did not show any effect of workload (CMT). A Tukey post-hoc test indicated that the 1 Hz condition significantly differed from the 4 and 10 Hz condition (for both  $p < <0.01$ ).

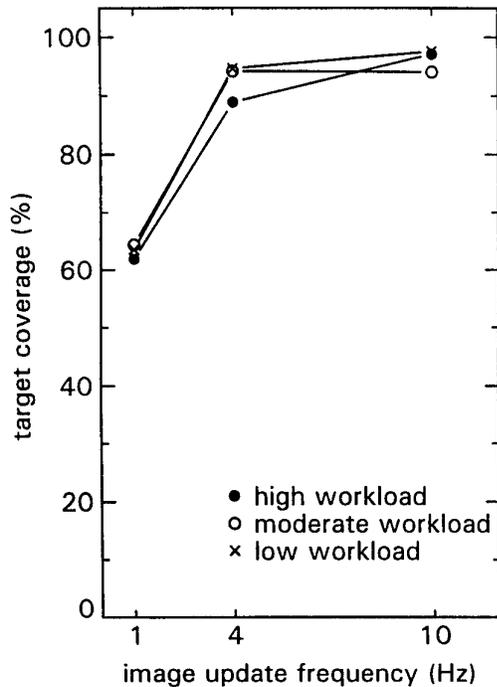


Fig. 1 Mean target coverage as a function of the sensor image update frequency and operator workload, averaged over the subjects.

### 3.2 Viewing error

In Fig. 2 the sensor viewing error is presented, for three image update and workload conditions, averaged over the subjects.

It can be seen that the viewing error was nearly negligible at image update frequencies of 4 Hz or more, and was increasing significantly at low update frequencies. According to a 3 (Update frequency)  $\times$  3 (Workload) ANOVA this effect was just significant [ $F(2,18) = 3.36$ ;  $p = 0.05$ ].

In the figure, the screen limits (e.g. the distance from screen-centre to screen-edges) are shown, indicating the visibility criterion of the tracking task. It can be seen that the viewing error only exceeded the screen limits at the lowest update frequency condition. This was also the only condition in which any effect of workload was found. The ANOVA did not indicate any significance of this effect.

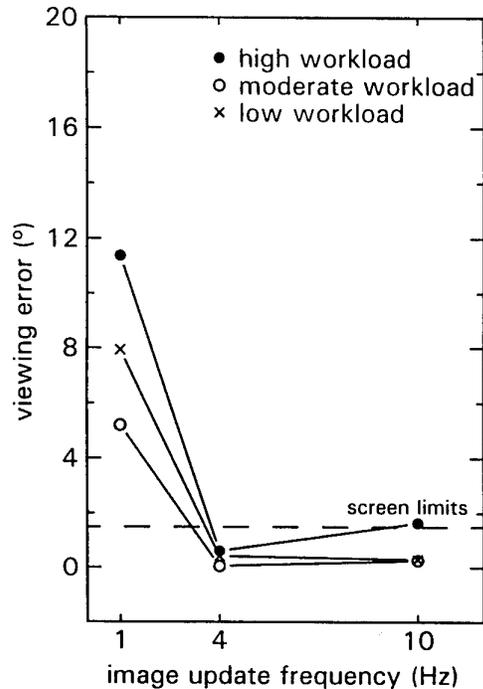


Fig. 2 Mean sensor viewing error as a function of the sensor image update frequency and operator workload, averaged over the subjects. The horizontal dashed area indicates the screen limits (distance from screen-centre to screen-edges).

### 3.3 CMT score

In Fig. 3 the percentage correct response of target-letter hits and count 3 target-letter hits are presented, for three image update and workload conditions, averaged over the subjects.

The results clearly show that the percentage correct response of target-letter hits was about 100% for all conditions, no matter the image update or workload condition. A 3 (Update frequency)  $\times$  3 (Workload) ANOVA did not indicate any significant effect or interaction.

The figure also shows that the average percentage count 3 target-letter hits was about 90% and had a tendency to decrease with low update frequencies. However, the ANOVA did not confirm this effect. The effect of workload is clear, the performance at high workload was about 10% less compared to the performance at moderate workload. This effect was significant [ $F(1,9) = 9.43$ ;  $p < 0.05$ ].

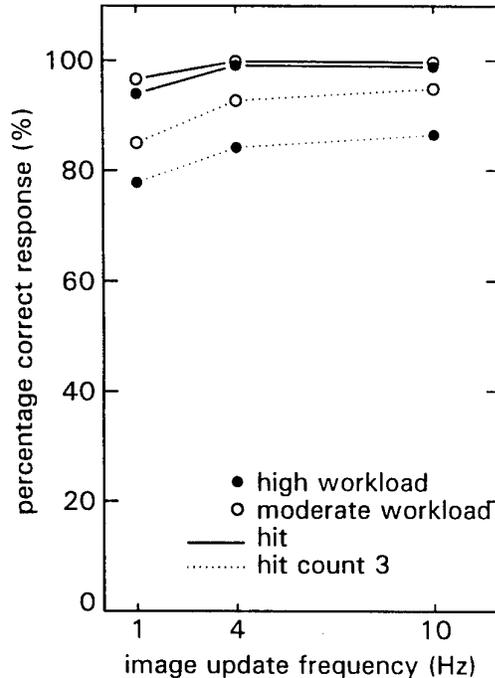


Fig. 3 Mean percentage correct response of target-letter hits and count 3 target-letter hits, as a function of the sensor image update frequency and workload, averaged over the subjects.

#### 4 DISCUSSION

As was expected, the experimental results showed a decrease of MUAV tracking performance with lower update frequencies of the sensor image. With 10 or 4 Hz, the mean coverage of the target remained at nearly 100% of the tracking time, but at 1 Hz this was only about 60%. This was caused by an increase of the viewing error, exceeding the field of view of the camera.

As was predicted by Wickens' multiple resource model, no significant decline in target coverage was found when the subjects performed the tracking task under moderate and high verbal/cognitive workload conditions. Only with 1 Hz update frequency the mean viewing error increased. Hence, Wickens' predictions on task performance were not completely valid with regard to the most difficult tracking condition. Tracking with low update frequencies probably required more central (mental) processing concerning the target's behaviour. This increasing demand of attention could not be rewarded, in particular not during high workload conditions, since the subjects were instructed to give primary attention to the verbal/cognitive task. This resulted in an increase of the mean viewing (tracking) error.

Verification of the subjects' verbal/cognitive task performance pointed out that this task was properly executed; the target-letter hits, as well as the count 3 target-letter hits remained unchanged over the workload conditions.

## 5 CONCLUSIONS AND SUGGESTIONS

The RNLN considers to perform a MUAV mission by multiple MUAV systems, in which multiple functions (track a target, supervise tactical information and multiple air vehicle status, communicate) have to be fulfilled simultaneously. In order to investigate the effect of workload on tracking performance, an experiment was conducted in which operators had to perform a MUAV supervisory control task. During this experiment, subjects had to track fast moving targets in an open sea situation with different image update conditions. In addition they had to perform a verbal/cognitive task under different workload conditions.

Results of the experiment show that moderate and even high workload conditions did not affect the mean target coverage of the sensor image. This was about 100% at image update frequencies of 4 Hz and more, decreasing to about 60% at 1 Hz update frequency. This may be explained by the fact that, in the latter case, the tracking task became more discontinuous, which demanded more attention for anticipation. Since the subjects were instructed to give primary attention to the verbal/cognitive task, this extra attention was not fully available, in particular not during high workload conditions. This resulted in an increase of the mean tracking error.

The fact that a significant tracking performance degradation was found at low image update frequencies, indicates that image update frequency is one of the crucial factors affecting operator performance. Many attempts are currently made to improve the MUAV downlink transmission bandwidth in order to increase information flow. However, high costs and technological limitations hamper the progress in this field (Schwartz et al., 1992; NATO, 1993; Rochus & Garcia, 1995; Van Breda, 1995). Since the decrease in operator performance is caused by lack of anticipation and orientation (Van Breda & Passenier, 1993), it should be investigated whether provisions for enhanced visual information may be a more efficient way to improve operator performance. This should not only concern improvement of the sensor image characteristics, but also improvement of the operator's awareness by depicting additional graphics information onto the sensor image ("synthetic image augmentation"). For example, artificial vehicle references, or synthetic perspective graphics of a "virtual landscape" as seen from the actual MUAV position, displayed at a high update rate (i.e. 60 Hz), may improve the operator's anticipation and orientation possibilities, and thereby enhance the tracking performance.

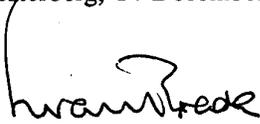
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Soesterberg, 14 December 1995

A handwritten signature in black ink, appearing to read 'L. van Breda'. The signature is written in a cursive style with a prominent loop at the end.

Ing. L. van Breda

## APPENDIX: Simulation Parameters

**Target area**

- Surrounded by sea: a horizontal plane of infinite size and dark grey colour.
- Sky: background of light bluish-grey.
- Small area: an area of uncertainty (AOU) of 100 nm<sup>2</sup> provided by cue; circular in shape.
- Large area: 1/3 of a sector, uncued. (A sector is defined as a 40° region, between 20 and 100 nm distance from ship; thus, 1/3 of a sector is approx. 1100 nm<sup>2</sup>.)

**Target**

- |                  |         |     |
|------------------|---------|-----|
| • class          | frigate |     |
| • length         | 100     | m   |
| • width          | 15      | m   |
| • height         | 4       | m   |
| • maximum speed  | 40      | kts |
| • turning radius | 400     | m   |

*Colour*

- Dark grey hull, lighter grey deck.
- Colours approach that of sea, linearly in RGB (voltages of red, green, and blue electron guns of monitor), as distance from UAV increases (to simulate atmospheric effects on image). At 10 km distance, ship and sea colours are identical, simulating zero visibility.

*Wake*

- Light grey at ship; approaches colour of water at tail; visibility reduces with distance from UAV (in same manner as ship does).
- Width is roughly equal to width of ship.
- Length is a function of ship speed (it lasts for 20 s; maximum is 417 m).

*Manoeuvring*

The ship always moves at its maximum speed. Every 10 s, the ship has a 50% probability of turning in a random direction. Once a turn is initiated, the duration of the turn is randomly chosen between 0 s and 10 s. The intention is to simulate a range between undisturbed straight navigation when the UAV is distant, and avoidance manoeuvres when the UAV is near. The latter assumes a worst-case scenario: the target pilot knows he is under scrutiny, and wishes to make his ship difficult to track.

## MUAV motion

### *Horizontal translations*

- maximum translational rate of  $\pm 120$  kts
- maximum yaw rate of  $\pm 3$  °/s
- acceleration control by longitudinal axis of position joystick or arrow keys (separate control only)
- rate of yaw control by lateral axis of position joystick or arrow keys
- first-order control system with 3-s time constant.

### *Vertical translations*

- constant altitude 6561 ft.

## Sensor/Gimbal

### *Azimuth (Yaw)*

- maximum rate of  $\pm 30$  °/s
- 360° range
- rate controlled by lateral axis of position joystick or arrow keys (separate control only)
- gain is proportional to FOV, allowing a constant sensitivity to input across all levels of zoom
- gain is proportional to *distance to footprint centre*, allowing a constant sensitivity to input across all distances.

### *Elevation (Pitch)*

- maximum rate of  $\pm 20$  °/s
- range of 20° to -120°
- rate controlled by longitudinal axis of position joystick or arrow keys
- gain is proportional to FOV, allowing a constant sensitivity to input across all levels of zoom
- gain is proportional to *distance to footprint centre*, allowing a constant sensitivity to input across all distances.

### *Field of view*

- maximum FOV of 46.7°
- minimum FOV of 3.0°
- FOV increase/decrease controlled by function keys.

## Coupled control

Single input device controls UAV yaw laterally and footprint speed longitudinally.

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