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**CRUSADER AUTOMATED  
DOCKING SYSTEM**

**Technology Support for the  
Crusader Resupply Team  
Interim Report**

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**MANAGED BY  
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FOR THE UNITED STATES  
DEPARTMENT OF ENERGY**

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## 1. INTRODUCTION

The U.S. Army and Team Crusader (United Defense, Lockheed Martin Armament Systems, etc.) are developing the next generation howitzer, the Crusader. The development program includes an advanced, self-propelled liquid propellant howitzer and a companion resupply vehicle. The resupply vehicle is intended to rendezvous with the howitzer near the battlefield and replenish ammunition, fuel, and other material.

The Army has recommended that Crusader incorporate new and innovative technologies to improve performance and safety. One conceptual design proposes a robotic resupply boom on the resupply vehicle to upload supplies to the howitzer. The resupply boom would normally be retracted inside the resupply vehicle during transit. When the two vehicles are within range of the resupply boom, the boom would be extended to a receiving port on the howitzer. In order to reduce exposure to small arms fire or nuclear, biological, and chemical hazards, the crew would remain inside the resupply vehicle during the resupply operation.

The process of extending the boom and linking with the receiving port is called docking. A boom operator would be designated to maneuver the boom into contact with the receiving port using a mechanical joystick. The docking operation depends greatly upon the skill of the boom operator to manipulate the boom into docking position. Computer simulations at the National Aeronautics and Space Administration have shown that computer-assisted or autonomous docking can improve the ability of the operator to dock safely and quickly.

Autonomous docking employs a sensory element and computer to determine the port location and maneuver the resupply boom into contact with the receiving port without direct operator intervention. The docking procedure could have several degrees or modes of operation. In manual mode, the docking is performed by viewing the port through a boom-mounted camera and controlling it using a joystick. Here the hand-eye coordination and judgment guide the path of motion of the boom. The automated system would be inactive in manual mode.

The first level of autonomous operation would be computer-assisted docking. In this mode, the automated system would be active in monitoring the boom position. The crew would still control all boom motion but could use the automated system to provide additional information to supplement its own. For example, the automated system might indicate the distance remaining to target, giving a continuous confirmation of the boom position.

The highest level of autonomous operation is autodocking. In the autodocking mode, the automated system would control the boom motion to dock. The operator would initiate the autodocking procedure and would monitor the progress. He could intervene at any time if an abnormal condition should arise.



## **2. PURPOSE**

This document describes the present status of the Crusader Autonomous Docking System (CADS) implemented at Oak Ridge National Laboratory (ORNL). The purpose of the CADS project is to determine the feasibility and performance limitations of vision systems to satisfy the autonomous docking requirements for Crusader and conduct a demonstration under controlled conditions. A statement of work for this task was completed and agreed to by Team Crusader, the Project Manager-Crusader, and ORNL. Work was initiated in June 1995. This document describes the progress on the project after approximately 3 months' effort, and it will specifically deal with Tasks A, B, and the first of three technology demonstrations planned for the project, Task D.1, the Table-Top Autodocking Demonstration. Each of these activities, as identified in the statement of work, is described in the following sections.

### **2.1 TASK A: PROJECT REQUIREMENTS ANALYSIS**

This review will divide the requirements into subgroups to include (1) performance/functional, (2) form factor, (3) hardening, (4) maintenance, (5) reliability, and (6) safety. A cursory study will be conducted of the components of the current automated docking system to evaluate them against the system requirements, and potential problem areas will be identified.

### **2.2 TASK B: CONCEPT SELECTION DOCUMENTATION**

The previously conducted autodocking technology market survey will be updated to reflect any relevant developments in industry. A review of the concept selection process will be completed in light of any developments, and the concept selection process documentation will be updated.

### **2.3 TASK D.1: TABLE-TOP AUTODOCKING DEMONSTRATION**

Pose determination algorithms will be developed and verified using the autodocking system being developed with a commercial table-top robot.





### **3. RESULTS OF THE PROJECT REQUIREMENTS ANALYSIS (TASK A)**

Team Crusader provided a list of requirements for the fielded system to be considered for the CADS project. Each of these requirements was extracted from the Advanced Field Artillery System (AFAS) Specification. The first activity of the CADS project, as described in Task A, was to divide the requirements into subgroups. The second activity of the task was to select equipment components from the current concept to evaluate against these requirements. Each of these activities is described in the following paragraphs. Also, the CADS currently being developed is described, specific system components are identified, and their vulnerability related to various requirements is assessed.

#### **3.1 SUBGROUPING OF REQUIREMENTS**

Team Crusader provided a listing of the CADS requirements extracted from the AFAS Specification. These requirements are included as a table in Appendix A. Each of the requirements was evaluated and categorized into subgroups. The appropriate subgroup for each of the requirements is identified in the table, and the requirements are listed with their respective subgroups. The most important requirements from the ORNL system development and demonstration standpoint were performance, form factor, and hardening. Maintenance, reliability, and safety are equally important in the fielded system; however, ORNL believes it is premature to assess the CADS prototype against these requirements. Because the algorithms and components of CADS are still developmental and subject to further revision, these factors can be more accurately evaluated after the development process has been finalized.

Considering then the performance, form factor, and hardening requirements as the highest priority, a preliminary assessment of each individual requirement was conducted to indicate which of the particular requirements might represent a problem in the fielded system and to what extent further consideration should be given in the ORNL assessment of that requirement. Some requirements were judged as being either ambiguous or not descriptive enough to be meaningful or were listed as TBD; these cases were not considered for the purposes of this study and were listed as NC (Not Considered). Some requirements were judged as having no applicability to the system being developed and were listed as NA (Not Applicable). Some of the requirements were believed to be satisfied by the current development system or easily achievable in the fielded system with current technology; these were listed as NP (No Problem Anticipated). And finally, some of the requirements were identified as needing further evaluation by ORNL and were listed as ER (Evaluation Required). Further evaluation consisted of testing conducted in the laboratory and/or discussions with commercial vendors to determine the commercial feasibility to satisfy the requirement. The table in Appendix A gives the subgroup category and preliminary assessment for each requirement.

In evaluating/testing the various aspects of the system it was considered imperative that the performance-related requirements be satisfied. It was also considered essential that the system satisfy or show a clear development path to the satisfaction of the physical

constraints (form functions) imposed. Hardening requirements were also considered important, but the capability of simulating most of the environmental conditions was neither possible nor practical for the development system. Therefore, the primary method of evaluating the feasibility of hardening the various components was through discussions with commercial vendors. Laboratory testing was limited because (1) only a few of the environmental characteristics could be evaluated in a conventional electronics laboratory and (2) the task budget would not allow system components to be destructively tested. Several of the environmental conditions were simulated and evaluated; however, the primary objective was the performance of the system under these conditions—not the environmental exposure of components. The extent of the further evaluation conducted is described in the following sections.

### **3.2 SYSTEM COMPONENTS IDENTIFICATION AND ANALYSIS**

ORNL selected commercially available, inexpensive components and used them to the greatest extent practical. A description of the system and its functionality is provided, and specific components are identified. While the selected components provided a cost-effective development system, they did not take advantage of commercially available hardened components already developed to meet many of the military specifications identified. Therefore, an analysis of the system components was conducted which considered any requirements that were questionable. This analysis consisted of consultations with commercial vendors and reviews of vendor literature. Additionally, miscellaneous laboratory testing was conducted to determine the capability of CADS to meet the performance requirements. Each of these areas, along with recommendations for further consideration, are described in the following sections.

#### **3.2.1 System Description**

CADS is a vision-based, remote pose determination method designed to accurately measure the position and orientation (pose) of the artillery receiving port from a remote location. The system measures the 6-D.F. position and orientation of a target port with respect to a vision sensor. Robustness and measurement quality estimates have been incorporated into the design to give high accuracy as well as to prevent the reporting of large positioned errors.

Autonomous docking requires the coordinated actions of (1) a robotic boom, (2) a control system to move the boom to the desired position, and (3) a sensory system to monitor the position of the boom and its destination. CADS provides the sensory information that enables an external robotic guidance control system to autonomously dock with a designated target.

CADS uses commercial, off-the-shelf components. The requirements of a production version of CADS were considered during the design and implemented when possible. Some requirements, such as power, weight, and volume constraints, were unknown at the time of development. Other factors, such as weather and environment, were anticipated in the basic design, which is extendible to an all-weather version. For example, CADS uses a low-cost video camera, but the CADS measurement algorithm should perform equally well with a militarized infrared camera.

CADS also uses a video camera mounted on the robotic manipulator to view the receiving port. The receiving port must be equipped with identification markers to distinguish

the intended target from other objects in the field of view. CADS, with its camera, forms the sensory elements for autonomously docking the robot with the target. The position and orientation of the target are sent to the control system, which directs the robot motion to the target (see Fig. 1).

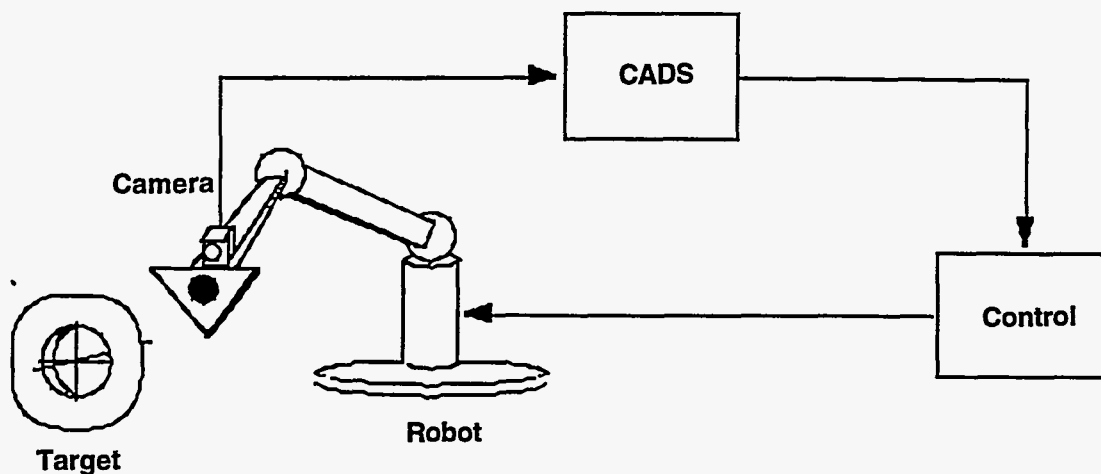


Fig. 1. Robot or Modular Artillery Ammunition Delivery System boom.

CADS was developed to demonstrate the feasibility of autonomously docking a robotic manipulator. It is designed to operate in conjunction with other devices in a client-server communications model over an Ethernet socket connection. Typically, the external device is the control system for the robotic manipulator. Pose data from CADS can be sent to the control system or displayed locally on a CRT screen.

The output of CADS is a coordinate vector containing the six pose parameters ( $x$ ,  $y$ , and  $z$  position and pitch, roll, and yaw angles) and a confidence factor. The coordinate vector is updated upon receipt of a triggering signal from the boom control system. The continuous update rate is approximately 1300 ms per pose vector.

CADS consists of five functional units: (1) target, (2) image formation, (3) target acquisition, (4) pose determination, and (5) pose display. The functional block diagram is shown in Fig. 2.



Fig. 2. Functional block diagram of CADS.

### 3.2.1.1 Target

CADS requires a special apparatus to uniquely identify the docking target. The target for CADS version 2 resembles a small "birdhouse" with six light-emitting diodes (LEDs) mounted along the perimeter of the front side. The LEDs, which are strobed at 12 Hz, mark the major vertices of the structure. The LEDs are driven by a custom-designed microprocessor board that controls the flash duration and frequency of the LEDs.

During initialization, the system reads a target data file from the disk. The data file contains a description of the LED coordinates. The pose algorithm uses this information to create an internal wire frame model of the target which is matched to the camera image. The target geometry can be reprogrammed to accommodate changes to the target.

### 3.2.1.2 Image formation

The target area is captured in video format by the image formation function. Image formation requires a video camera, lens, and a digitizer. The camera is a commercial off-the-shelf unit intended for operation in the visible spectrum. The camera format is  $512 \times 512$  progressive scan. The focus element is a 6-mm fixed focal length lens. The video signal is sent to a commercial image processing board in the CADS chassis for digitization and processing.

### 3.2.1.3 Target acquisition

The target acquisition function finds the coordinates of the center of each LED in the camera image. The LEDs are first segmented from the image background using a digital demodulation technique. The resultant image is thresholded and labeled. The centroid of each object is determined from the moments of the binary image. An analysis of each object is performed to verify that it is an LED.

The digital demodulator is necessary because the LED modulation is asynchronous to the camera. The LEDs are modulated to increase the target detectability in the presence of background clutter and noise. The 12-Hz modulation frequency was chosen to minimize modulation artifacts with the 30-Hz video sampling rate.

### 3.2.1.4 Pose determination

The pose determination function calculates the position and orientation of the target based on the coordinates of the target LEDs which mark the vertices. The coordinates of the LED markers are generated in the target acquisition function and passed to the pose determination function.

A predefined wire-frame model of the target is stored in the CADS memory. The model is a representation of the size and shape of the physical target and is generated during initialization from a data file on disk. The data file contains a list of the LED coordinates as measured on the target.

The LED locations of the digital wire-frame model are positioned to match the LED coordinates from the target acquisition function. The match is accomplished through a least squares regression to minimize the spatial errors. After the regression has converged, the target position and orientation parameters are available.

When a request for pose data is received from an external device, CADS will reply with the next available measurement. In the normal operating mode, the pose measurements are made continuously. A pose request may be received at any point in the measurement cycle. Therefore, the response latency, or the elapsed time before the CADS responds to the pose

request, is variable. The maximum latency is the pose update rate of 1300 ms, and the minimum latency is near zero.

#### **3.2.1.5 Pose display**

The pose data can also be displayed on a local CRT screen to assist the operator during automated docking operations. An interface was developed to present all pertinent docking parameters to the operator. The display provides instrument gauges to indicate the position and orientation of the target. A video window shows a live image from the boom camera, while another window gives a third-person representation of the relative position of the boom and the target. The game-like icons or widgets indicate all 6 D.F. of the boom.

### **3.2.2 Assessment of CADS Components**

This section is divided into four subsections. The key components of the system (described in Sect. 3.2.1) and how they meet the overall requirements are discussed in Sect. 3.2.2.1. To verify the performance aspect of the requirements, preliminary environmental testing was conducted at ORNL (see Sect. 3.2.2.2). To satisfy the hardening aspect of the requirements, a vendor survey of the commercial manufacturers of camera and infrared (IR) diodes was conducted (see Sect. 3.2.2.3). Finally, Sect. 3.2.2.4 evaluates the specific requirements and recommendations based on Sects. 3.2.2.2 and 3.2.2.3.

#### **3.2.2.1 Key CADS components and requirements subgrouping overview**

The autodocking system, described in Sect. 3.2.1, has the following components: (1) camera, (2) IR diodes, (3) Datacube MV 200, (4) CRT terminal, and (5) VME bus. Crusader will incorporate multiple computer and electronic components which will need to be hardened to military specification before use. The display interface, the Datacube, and the VME bus of the CADS are typical electronic components and will not be considered further since they impose no additional requirements unique to Crusader. The design team for the fielded Crusader will have expertise in hardening these types of electronic components, and no problem is envisioned.

The camera and IR diodes were, therefore, the only items considered. This assessment consisted of an evaluation of their ability to meet the performance, form factor, and hardening requirements identified.

Due to their relative small sizes, camera and IR diodes do not impact the form factor requirements identified and therefore no further form factor consideration is given.

#### **3.2.2.2 Performance testing**

The objectives of the performance tests were to (1) characterize the baseline performance of CADS and (2) make a qualitative assessment of performance under adverse conditions, notably rain and fog.

The tests were conducted during July 1995 at ORNL. The facilities at the site limited the nature and extent of the tests that were feasible. In particular, the facility had no means to control or measure the degree of particulate spray for the simulated weather conditions. All tests took place indoors, and precipitation was artificially induced to simulate rain and fog. The test exercise was not intended to be exhaustive, and additional tests may be appropriate in the future.

The procedure included testing under ideal conditions to establish a performance baseline and under simulated adverse conditions for comparison. The baseline performance factors that were measured are execution speed, relative position accuracy, and continuous operation. The adverse environmental test conditions included rain, water droplets on the lens, fog, and vibration.

### Refresh Rate

The execution time required to calculate the docking pose is dependent upon the two primary signal processing algorithms: target acquisition and pose determination. The target acquisition algorithm requires 20 consecutive video frames in order to extract the illuminated vertex markers from the background. For the camera sampling rate of 30 frames per second, the minimum time to capture 20 frames is 670 ms. The pose determination algorithm is recursive, so the time is dependent upon the number of iterations needed. The pose determination algorithm can be run on the master CPU or the optional arithmetic accelerator board. The pose determination normally takes 400 to 700 ms to complete. The typical total time to calculate target pose is 1300 ms using the CPU and 1000 ms using the accelerator.

### Accuracy

The absolute position accuracy of CADS is not well described due to the difficulty in independently measuring the position of the docking target and the camera in 3-D space. CADS measures the vector distance from the camera coordinate origin to the target coordinate origin. The camera coordinate origin lies inside the lens body and is physically inaccessible, and the target coordinate origin is a point in free space at the center of the docking aperture. The ethereal nature of the two origin points makes direct physical corroboration of the measurement impractical.

In practice, absolute positional accuracy has little meaning for docking. Of greater importance is the relative positional accuracy which can be measured indirectly by comparing the change in position reported by CADS after a known change in the camera position. This is accomplished by mounting the camera on a calibrated translation stage, such as the table-top robot, and viewing the target. The position of the target is used as a reference point while the camera is then moved a known distance from the target. After the camera is moved, the target pose is determined and recorded. The position measured by CADS is compared to the actual position as read from the robot encoder. The measurement error in percent of the actual value is given by the familiar equation:

$$\text{Error} = \left[ \frac{r(\text{measured}) - r(\text{actual})}{r(\text{actual})} \right] \times 100 \quad , \quad (1)$$

where  $r$  is the position coordinate of the camera.

For this test, the camera was positioned perpendicular to the target and moved in 5-mm increments toward the target. A total of 30 measurements were recorded, beginning at a distance of 400 mm and ending at 105 mm. The measurement error was computed according to Eq. 1. The CADS mean positional error was  $-0.3\%$ , the median error was  $-0.35\%$ , and the maximum error magnitude was  $0.9\%$ .

The ultimate test of relative measurement accuracy is how closely the robot arm can be brought to the desired docking position. For a second test, the docking aperture of the



version 2 target was reduced to provide approximately 1-mm clearance when the robot is in docked position. The robot was randomly positioned in its work space, and automated docking was initiated. The experiment was considered successful if the robot was docked without touching the target aperture. The experiment was successfully repeated several hundred times.

### Continuous Operation

The purpose of the continuous operation test was to operate CADS over an extended period of time while recording the number of valid and invalid pose measurements that were made. The intent of this test was to determine the probability that a request for pose would be successful and therefore establish a baseline indication of short-term system reliability under ideal conditions.

In the current configuration, CADS generates a pose status flag indicating whether or not the pose calculation is valid. A FALSE flag may be caused by two or more undetectable LED vertex markers. Markers are undetectable when another object blocks the camera view. The markers are also undetectable if their intensity at the output of the CADS internal digital demodulator is below a fixed threshold.

When the image markers do not fit the stored target model, the residual errors in the least squares fit can exceed a predetermined threshold, thus triggering the FALSE flag, indicating an invalid pose. The invalid pose does not disrupt operation, and the system will continue to acquire pose measurements.

For this test, the camera was randomly positioned facing the target. CADS was set to continuous acquisition mode. The pose status flag was monitored and recorded for each attempted acquisition. Because the camera was positioned to have an unobstructed view of all vertex markers, a false indication on the pose status would be the result of an anomaly in the CADS signal processing pipeline, causing a reduction of the marker intensity.

The system was placed into continuous acquire mode and left unattended overnight or over weekends. At the conclusion of each test, a pose status flag histogram indicating the number of pose attempts and failures was recorded. The camera was repositioned, and the tests were repeated. As shown in Table 1, there were 236,640 pose attempts recorded over a 5-d period, with one invalid pose recorded during that period.

**Table 1. Continuous operation**

Date	Total attempts	Unsuccessful
7/14/95	37,035	0
7/17/95	161,500	1
7/18/95	38,105	0
Total	236,640	1

### Obstructed View

In the obstructed view test, the camera and target were subjected to simulated weather conditions to make a preliminary assessment of the CADS performance under adverse

conditions. The system performance under simulated weather conditions should be a predictor of performance under actual outdoor conditions.

Atmospheric effects were introduced to simulate various weather conditions likely to be encountered in the field. Rain was simulated by spraying water with an atomizer. The spray was directed onto the lens, onto the target, and in the air between the camera and target. Fog was simulated using a bed of dry ice beneath the camera field of view. A small-amplitude vibration was introduced in the lateral axis to simulate engine vibration. Examples of the target obtained from the camera under various weather conditions are given in Figs. 3–8.

The camera was positioned parallel to the target and facing it 350 mm away. The camera position was held fixed, and CADS was put in continuous acquire mode. For each environment condition, CADS performed a sequence of 25 pose measurements. The six pose parameters reported for each measurement were recorded. The mean, standard deviation, and minimum and maximum values were computed from the 25 measurements.

We define precision and accuracy to be figures of merit, where precision is given by the standard deviation and accuracy by the measurement error on the Z axis. Here we use the Z axis (distance to target) to describe accuracy because distance is an extrapolated value and should be the least accurate of the pose parameters giving a worst-case value for accuracy. Additionally, because the camera was centered normal to the target origin, the actual values for the other five pose parameters were near zero. The measurement error calculation is meaningless when actual values are zero.

The results of the obstructed view test are given in Table 2, which also lists the standard deviation and mean error values for the various test results. Detailed test results are given in Appendix B.

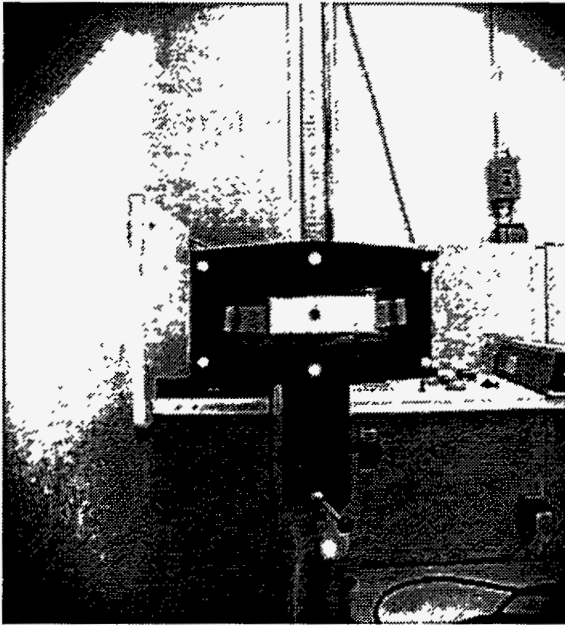
**Table 2. Test results summary**

Condition	Baseline	Light rain	Fog	Droplets on lens	Night fog	Lateral vibration
Standard deviation (mm)	0.245	0.415	1.79	0.365	1.45	0.359
Mean error (%)	-0.11	0.03	0.51	0.31	0.61	-0.023

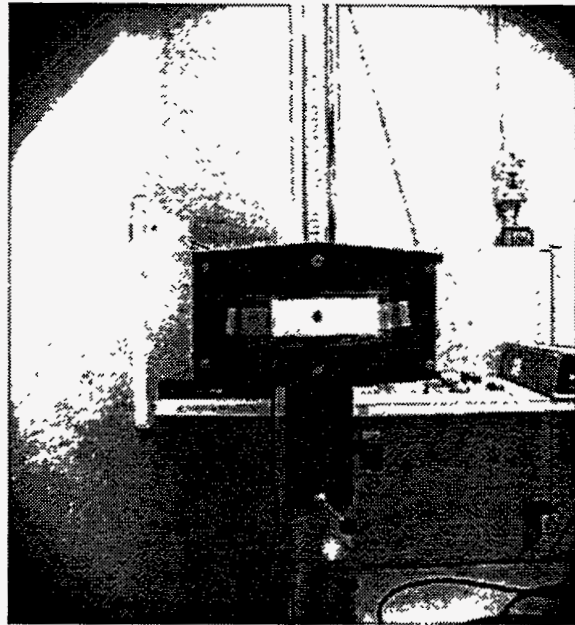
## Conclusions

The test results for CADS are encouraging. Under laboratory conditions, the prototype is reasonably fast, accurate, and reliable at this point in the system development. The system can acquire the docking target and compute the 3-D position and orientation of the target relative to the camera in approximately 1 s. The measurement error is less than 1% of the full-scale reading. The system has operated for nearly 80 h with no failures and one invalid pose measurement.

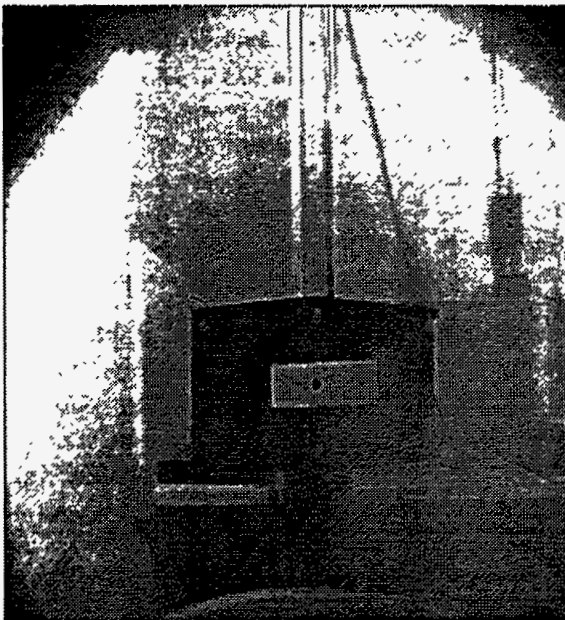




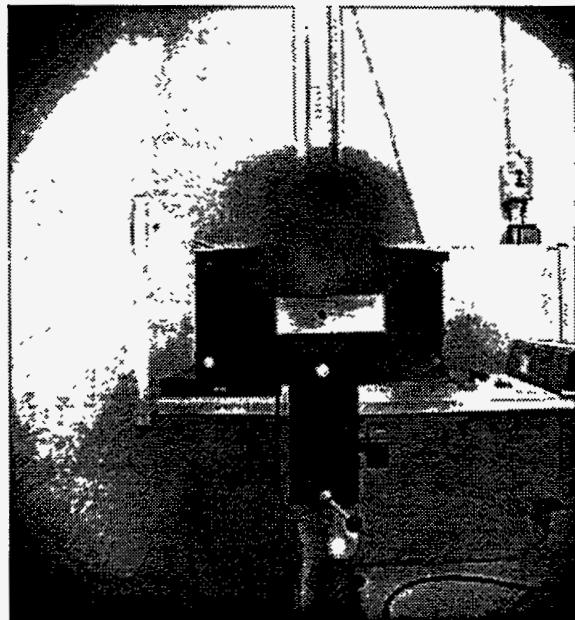
**Fig. 3. Baseline.**



**Fig. 4. Light rain.**



**Fig. 5. Fog.**



**Fig. 6. Droplets on lens.**

CADS is reasonably immune to the simulated weather disturbances. When operating under simulated adverse weather, the system continued to operate but with an increase in the measurement variability.



Fig. 7. Night fog.

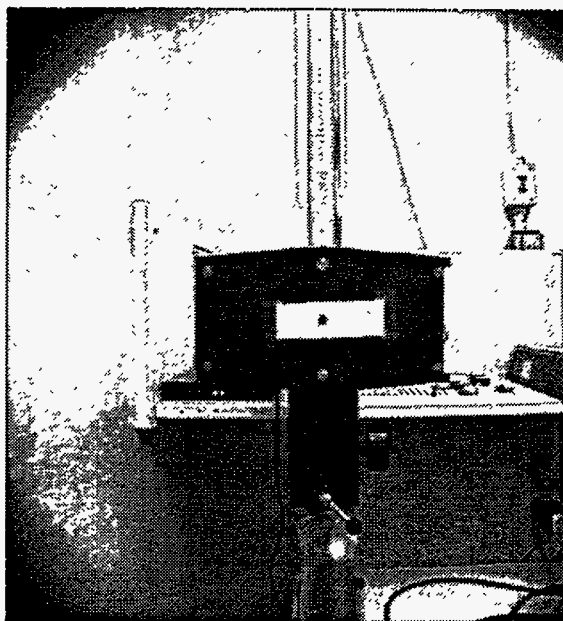


Fig. 8. Lateral vibration.

Under ideal conditions, the Z axis standard deviation was 0.245 mm and the measurement error was  $-0.11\%$ . Under simulated fog at night, the Z axis standard deviation increased to 1.45 mm and the measurement error also increased to  $0.61\%$ . In all simulated weather conditions, even with water droplets on the lens, CADS produced valid pose measurements but with reduced precision and accuracy. The question of how much degradation can be tolerated for normal operation was not addressed by these tests.

### 3.2.2.3 Environmental compliance of commercially available hardware

In considering the hardening requirements, vendors of commercially available charged-coupled diode cameras and IR diodes were contacted for information. Here, emphasis was placed not on whether a particular camera could completely satisfy all the requirements, but whether it had previously encountered and met similar requirements for its other clientele. Some of the camera vendors had already dealt with the specific military applications and were aware of similar hardening requirements. Listed below are some of the camera manufacturers and their typical hardening specifications:

#### Subtechnique Inc. [Phone: (703) 212-0080]

Many cameras are available from this vendor working both in the visible and IR spectrum. The vendor offers a separate pressurized enclosure that can handle the following:

1. Operating temperature:  $-40$  to  $65^{\circ}\text{C}$  and Storage:  $-54$  to  $70^{\circ}\text{C}$
2. Altitude: Meets MIL-E-5400T
3. Humidity: 100% meets MIL-E-5400T
4. Sand, dust, fungus, salt atmosphere, vibration, and shock: Meets MIL-E-5400T

**Sekai International [Phone: (310) 921-7775]**

Many broad-band high-resolution cameras are featured by this vendor. Some of the environmental specifications the cameras can tolerate are as follows:

1. Operating temperature: -40 to 65°C and Storage: -55 to 80°C
2. Altitude: MIL-E-5400T
3. Humidity: 5 to 90% RH (noncondensing)
4. Vibration: 7 G (Universal Gravitational Constant) RMS 15 to 2000 Hz
5. Acceleration: 12 G in all axes
6. Shock: 9 G, 11 ms, half-sine, 3 shock each direction and 20 G, 11 ms, half-sine, 1 shock in each direction
7. Camera is normalized after 1 h of cold soak, and 24-h soak will not materially affect turn-on/warm-up characteristics. The cameras are also Mil Black anodized on exterior surfaces.

**Videospection, Inc. [Phone: (801) 568-1742]**

The vendor has previous experience dealing with military, aerospace, and Army. The environmental hardening of the camera is listed as follows:

1. Operating temperature: -45 to 60°C and Storage: -50 to 80°C
2. Vibration: Exceeds Mil-Std.
3. Shock: 100 G, 11 ms, 3 axis
4. Pressure: 15,000 psi and Depth Rating: 30,000 ft. The camera is housed in a stainless steel enclosure and has heating coils to prevent fogging and sluggish operation due to cold temperatures. The camera is also hermetically sealed.

IR diodes used in the development were LTE-5208A made by Liteon. The diodes have an operating and storage temperature rating of -55 to 100°C. They also conform to the environmental and reliability for lifetime Military Specifications 883, 750, 202, and 19500.

**3.2.2.4 Reevaluation of the specific requirements and recommendation**

A cursory survey was conducted to evaluate the hardening capability of manufacturers of the commercial camera and IR diodes. The laboratory testing of the CADS system under environmental conditions, as discussed in Sect. 3.2.3, was also considered. With this various information, the requirements in Sect. 2.1 classified as ER (Evaluation Required) were further reviewed in Table 3.

To summarize, once the final selection process and the requirements based on performance are finalized, the cameras and IR diodes may have to be custom hardened. Table 3 is intended to show the familiarity of the commercial manufacturers of camera and IR diodes in meeting many of the military specifications.

Table 3. Requirements and their considerations

Requirement	Topic	Comment
3.7.1.2.19.1.1	Autodock time requirements	Will be verified during the autodocking demonstration in November 1995.
3.7.3.2.9.4-2	Automatic docking initiation and control	With crew having visual feedback and docking and resupply accomplished automatically, this requirement will be satisfied.
3.2.6.1.1.10	Rain intensities (P)	Limited testing on rain effects as described in Sect. 3.2.3 gave satisfactory results. Final fielded system must be tested to verify performance during all conditions listed in the requirement.
3.2.6.1.1.6	Snow conditions (P)	Not evaluated by ORNL. Needs further evaluation.
3.2.4.2.4-1	Temperature considerations	Vendor information on the cameras and IR diodes indicates that there should be no problem in satisfying this requirement.
3.2.4.2.4-2		
3.2.6.1.1.1		
3.2.6.1.1.3	Relative humidity	Hermetic seals provided on the camera provide adequate protection which should be sufficient to satisfy the requirement.
3.2.6.1.1.4	Atmospheric pressure	Vendors have demonstrated ability to manufacture cameras far exceeding the requirement. Hence, this requirement can be easily met.
3.2.6.1.1.5	Surface elevation	Cameras conforming to MIL-E-5400T specifications are commercially available. Satisfying this requirement should not be difficult.
3.2.6.1.1.7	Icing condition	Needs further evaluation.
3.2.6.1.2.1	Road shock	Commercial camera manufacturers indicate that there will be no problem satisfying this requirement.
3.2.6.1.2.2	Vibration	No problem envisioned in meeting the requirement.
3.2.6.1.2.3	Fire shock	Camera manufacturers make products that can easily withstand 8 to 10 G. There are also vendors that can make cameras that withstand 100 G. Since fire shock magnitude is not known, further evaluation is necessary, but envision no problem in meeting this requirement.
3.2.6.1.2.4	Lightning fields	Further evaluation required.
3.2.6.2.1.1	Storage temperature	Cameras and IR diodes have no problem satisfying this requirement.
3.2.6.2.1.2	Storage humidity	No problem anticipated for camera.
3.2.6.2.1.3	Transport elevation	No problem envisioned for camera.
3.2.6.1.1.10	Rain intensities (H)	Vendors with experience in underwater cameras can meet this requirement. Hence, this hardening requirement can be met by commercial vendors.
3.2.6.1.1.6	Snow conditions (H)	Needs further evaluation.
3.2.6.1.1.7.1	Ice fog (H)	Needs further evaluation
3.2.6.1.1.8	Sand and dust (H)	Cameras and IR diodes are capable of meeting this requirement.

## 4. CONCEPT SELECTION DOCUMENT (TASK B)

A feasibility report entitled "Autonomous Docking for the Modular Artillery Ammunition Delivery System," was submitted to the Army in September 1993. Due to the new direction that is currently being pursued with Team Crusader, ORNL was asked to update the information on any current developments in this field. With this in mind, a literature survey of the docking technology was performed. A sensor concept selection was provided in the earlier document.

### 4.1 LITERATURE SURVEY UPDATE

A literature survey was conducted by searching for key words: *autonomous docking*, *robotic guidance*, *3-D imaging*, *object tracking*, and *visual servoing* in journals and conferences published between the periods of January 1994 and June 1995. About 103 articles were found dealing with the these topics.

Of the 103 articles, 62 of the authors used vision as the primary sensor in accomplishing the task. There were about 10 articles that dealt with sonar sensors, 2 articles that dealt with laser range sensors, and 2 with radar. Other articles were not directly concerned with the use of sensor applications and implementations, but with high-level motion planning, sensor fusion, hierarchical model for a given task model, etc.<sup>1-6</sup>

Sonar sensors were used mostly for path planning problems inside a building. Since the sensor relies on the reflected sonar beam, the surface characteristics greatly determine its use. It generally requires a planar surface it can track or follow. Ability of the sonar sensor to recover shape is not very good. Due to these inherent problems, it will have difficulties isolating the vehicle from the image and recognizing the port once the vehicle is identified for the autodocking task.

New developments in the area of laser range sensors make them an attractive option. Barry<sup>7</sup> compares the laser range sensors by three manufacturers. The time-of-flight laser radar has 6-cm resolution at 15-m distance, while the amplitude modulated laser has 1.8-cm resolution at 10-m distance. The newest development in this field, frequency modulated laser radar, the beta version which is to be released September 1995, will have a resolution of 0.5 mm at 15 m. Due to this great pace of improvement in the resolution, a closer look at laser range sensor is warranted. Although the spatial resolution of laser range images is not as good as that of video cameras, the information obtained has some advantages.

The laser range sensors give depth information which can be easily used to reconstruct 3-D images of the world. The lack of spatial resolution of the range images is amply compensated by the depth information provided that is lacking in video images. Using stereo camera for video causes correspondence problems, which does not lend itself to easy depth information. If the docking port has some distinguishing characteristics (e.g., the port is made of 2-in.-thick metal projected out of the Crusader chassis), a range image can be advantageous by quickly distinguishing it from the surrounding. The same method can also be used to easily identify Crusader from its background. The depth gives a feeling of the size of a particular object in an image.



A negative aspect is that a good reflective surface (e.g., chrome-plated parts) will cause inaccurate readings from the laser range sensor. Once the image is obtained, most of the image processing algorithms (e.g., edge detection, segmentation, thresholding, etc.) remain the same as the ones used for a regular video image. This additional information is reflected in the updated Table 4 of the comparison of various sensory methods for autodocking.

**Table 4. Comparison of autodocking sensors**

Requirements/Sensor type	Video	Laser	Ultrasonic	Radar
Passive sensing	H	L	L	L
Passive target	H	H	M	M
Manual compatibility	H	M	L	M
Range	H	H	M	L
Accuracy	H	H	M	L
Reliability	H	H	H	H
Environmental	M	H	L	H

Note: L = Low, M = Medium, and H = High.

Table 4 shows that due to the close ratings for video and laser methods, an alternative approach to the video-based autodocking is to use laser range radars. At the time CADS was designed, the resolution of laser range cameras was insufficient for autonomous docking. Since that time, significant improvements in laser range cameras have been seen. The rapid pace of development will likely make laser range cameras a viable alternative to video cameras within 18 months.

A directly measured range image, such as that generated by a range camera, has significant advantages over the indirect range image from the video camera. The directly measured range image has significant advantages in pose determination and consequently in autodocking. The CADS pose determination algorithm was designed to utilize range data derived from either a laser camera or a video camera.

One potential benefit of the range camera is that the target markers used to identify the target and to calculate range information would not be needed because the laser camera is self-illuminating. At present, ORNL does not plan to incorporate a laser range camera into the prototype CADS. At the discretion of Project Manager-Crusader, however, ORNL could initiate a program to acquire a recent generation laser range camera and integrate it with the existing CADS pose determination algorithm.

## 5. TABLE-TOP AUTODOCKING DEMONSTRATION (TASK D.1)

A table-top implementation of autonomous docking was developed to demonstrate the feasibility of automated docking on a small-scale model. The purpose of the table-top demonstration was to gain experience and confidence into autodocking vision systems prior to integration with the Modular Artillery Ammunition Delivery System (MAADS) arm. The table-top demonstration allowed the engineers to test the vision system independently of the MAADS arm, which was still under development. This approach allowed for the parallel development of the two major components needed for MAADS autodocking.

The equipment used in the table-top demonstration includes (1) the CADS vision system, (2) custom fixtures with LED markers to simulate the MAADS docking port, (3) Mitsubishi RV-2 robot manipulator to simulate the MAADS arm, (4) Silicon Graphics workstation to simulate the MAADS control system, and (5) interfaces between the components (see Fig. 9).

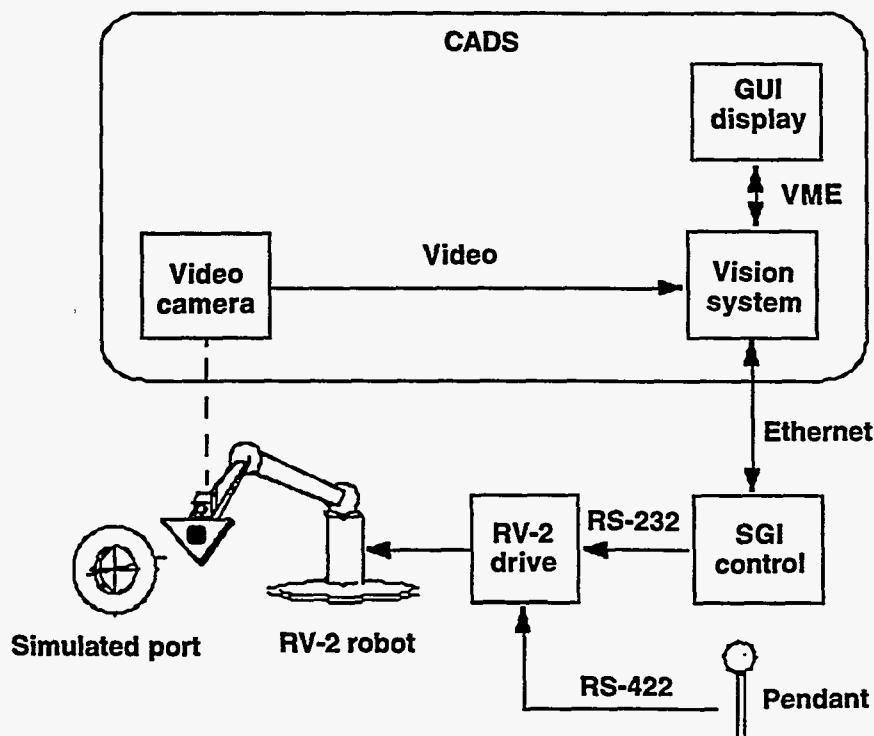


Fig. 9. Table-top demonstration equipment diagram.

For the table-top demonstration, the gripping end effector on the robot was detached and replaced with a docking head. The robot docking head included a camera mounting bracket and a 5-mm-diam, 120-mm-long rigid aluminum probe.

### 5.1 TARGET

The docking target used in the table-top demonstration is a seven-sided polygon that measures 208 mm wide  $\times$  102 mm high  $\times$  160 mm deep. A 15-mm aperture located in the center of the front faces is the docking port. The 8-mm-diam LED markers are mounted at the four corners and along the center axis. The target is mounted to a simple elevator stand that allows positioning the target in six axes (see Fig. 10).

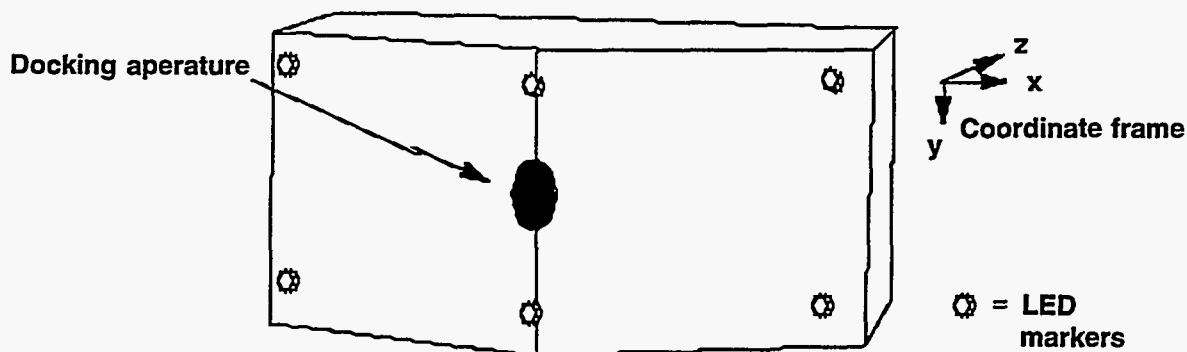


Fig. 10. Table-top docking target.

In a simulated docking exercise, the robot and target are placed in an arbitrary starting position. The robot must face the target such that the target LEDs are within the camera view. If the target is not within the camera field of view, CADS will issue an error message and abort the procedure. An error condition is also generated if a docking command is given when the target is beyond the reach of the RV-2.

### 5.2 ROBOT PATH

The autodocking algorithm uses two pose measurements to dock. An initial measurement is made to determine the coarse pose of the target. From the coarse pose, an intermediate position is found. The intermediate position is perpendicular to the docking aperture and 175 mm away along the central axis. The robot is moved to the intermediate position where a final pose, straight-on to the target, is taken. The docking solution is computed from the final pose, and the robot is directed to dock (see Fig. 11).



## Top view

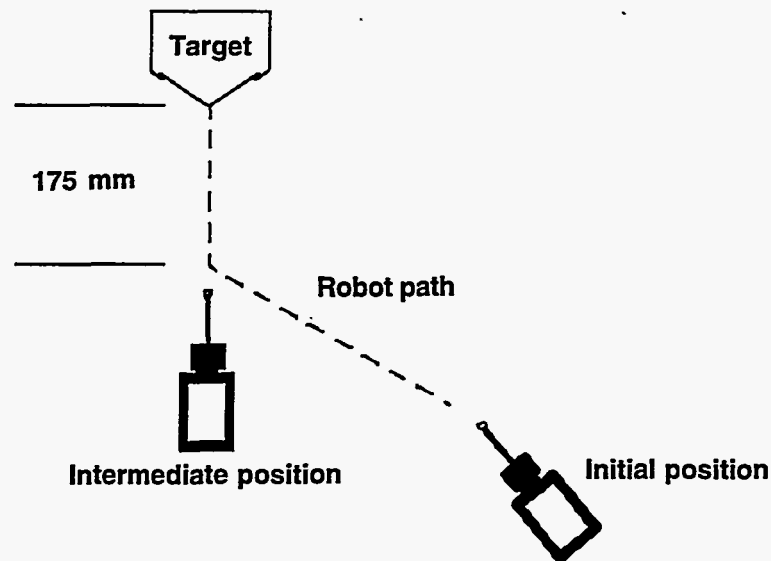


Fig. 11. Robot path for autodocking maneuver. Target pose is taken at initial and intermediate robot positions.

### 5.3 STATUS

Task D.1, Table-Top Autodocking Demonstration, is complete. CADS became operational for small-scale autonomous docking on June 8, 1995. An initial demonstration of the CADS functionality was given to the Office of the Project Manager-Crusader representatives.

A videotape of the table-top autodocking demonstration is available and has been shown to the Crusader team members in Burlington and Minneapolis.



## REFERENCES

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**APPENDIX A**  
**CRUSADER AUTOMATED DOCKING SYSTEM REQUIREMENTS**

## Crusader Automated Docking System Requirements

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.3.11-1	P	The system shall have a minimum of 60% computer reserve capacity (150% growth) for memory, processor throughput, input/output (I/O) channels, and I/O throughput. Computing requirements and I/O requirements are needed to determine impact on overall system needs.	NP
3.3.11-2	P	The computer memory reserve capacity for both read only memory and random access memory shall be measured separately at the Computer Software Configuration Item (CSCI) level. Computing requirements and I/O requirements are needed to determine impact on overall system needs.	NP
3.3.11-3	P	The processor and the I/O channel throughput reserve capacity shall be measured at the peak (full operational) loading conditions over a specified period of time, as determined by the characteristics of the operational mission at each CSCI and system level. I/O requirements are needed to determine impact on overall system needs.	NP
3.3.2.1-2	P	Each component, assembly, and subsystem, when installed as a complete system and operating as intended, shall cause no undesirable response, malfunction, or degraded performance of any other component, assembly, or subsystem installed in or associated with the system.	NP
3.3.2.1-3	P	No component, assembly, and subsystem shall likewise be affected when other component, assembly, and subsystems are singularly or collectively operated.	NP
3.3.6.13-1	P	The lighting system shall be in accordance with MIL-STD-1179 (Notice 3).	NP
3.3.6.13-4	P	All external lights shall be mounted in protected locations when possible.	NP
3.6.2.3.2-1	P	The system shall support an embedded training capability to accomplish sustainment training in garrison and field environments. Proposed software requirements are desired.	NC
3.7.1.2.19.1.1	P	The subsystem shall be capable of automatically docking in less than 3.5 min. The automated docking function begins when the AFAS and FARV are within 8 m, respective resupply ports are facing each other, and the FARV initiates docking. It is completed when the FARV has mated to the port on the AFAS and all connectors have been made.	ER

\* These refer to AFAS specification paragraphs.

\*\*P = Performance, F = Form Factor, H = Hardening, M = Maintenance, R = Reliability, and S = Safety.

\*\*\*NA = Not Applicable, NC = Not Considered, ER = Evaluation Required, NP = No Problem Anticipated.

### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***																												
3.7.3.2.7.10.2-4	P	The C3 subsystem shall provide sufficient vision to enable docking/resupply orientation.	NP																												
3.7.3.2.9.4-1	P	The subsystem shall provide the crew direct control of the resupply process without requiring the crew members to leave their stations.	NP																												
3.7.3.2.9.4-2	P	This process shall be automated to the maximum extent possible.	ER																												
3.2.6.1.1.10	P	<p>Rain intensities as specified below:</p> <table> <tr> <th>Period</th><th colspan="2">Amount</th><th>Wind speed (intermittent)*</th></tr> <tr> <th></th><th>(in.)</th><th>(mm)</th><th>(knots/kph)</th></tr> <tr> <td>1 min</td><td>0.45</td><td>11.4</td><td>35/63</td></tr> <tr> <td>5 min</td><td>1.00</td><td>25.4</td><td>35/63</td></tr> <tr> <td>10 min</td><td>1.50</td><td>38.1</td><td>35/63</td></tr> <tr> <td>1 h</td><td>5.50</td><td>139.7</td><td>35/63</td></tr> <tr> <td>12 h</td><td>9.50</td><td>241.3</td><td>35/63</td></tr> </table> <p>The larger drop sizes tend to be associated with the greater intensities. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.</p>	Period	Amount		Wind speed (intermittent)*		(in.)	(mm)	(knots/kph)	1 min	0.45	11.4	35/63	5 min	1.00	25.4	35/63	10 min	1.50	38.1	35/63	1 h	5.50	139.7	35/63	12 h	9.50	241.3	35/63	ER
Period	Amount		Wind speed (intermittent)*																												
	(in.)	(mm)	(knots/kph)																												
1 min	0.45	11.4	35/63																												
5 min	1.00	25.4	35/63																												
10 min	1.50	38.1	35/63																												
1 h	5.50	139.7	35/63																												
12 h	9.50	241.3	35/63																												
3.2.6.1.1.6	P	<p>Snow conditions consisting of falling snow crystals of 0.05 to 19.8 mm diam (0.002 to 0.78 in. diam) of sufficient density to accumulate 10 cm/h (4 in./h). Snow conditions shall persist for extended durations with maximum snow loads of 98 kg/m<sup>2</sup> (20 lb/ft<sup>2</sup>). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.</p>	ER																												

\* These refer to AFAS specification paragraphs.

\*\*P = Performance, F = Form Factor, H = Hardening, M = Maintenance, R = Reliability, and S = Safety.

\*\*\*NA = Not Applicable, NC = Not Considered, ER = Evaluation Required, NP = No Problem Anticipated.

### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.1.1.7.1	P	Ice fog consisting of suspended ice crystals averaging 5 to 20 $\mu$ diam of sufficient density to limit visibility to 1.5 m (4.9 ft). Susceptibility of electro-optical systems to ice fog shall be minimized. Ice fog generated by the system's engine exhaust shall not interfere with electro-optical equipment. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NC
3.2.6.1.1.8	P	Sand and dust. Particle concentrations of 1.06 g/m <sup>3</sup> ( $6.61 \times 10^{-5}$ lb/ft <sup>3</sup> ) with wind speeds up to 18 m/s (59 ft/s) at a height of 3 m (10 ft). Particle sizes shall range from less than 74 $\mu$ m diam ( $2.91 \times 10^{-3}$ in. diam) to 1000 $\mu$ m ( $3.94 \times 10^{-2}$ in.) with the bulk of the particles ranging from size to 74 to 35 $\mu$ m ( $2.91 \times 10^{-3}$ to $1.378 \times 10^{-2}$ in.). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NP
3.2.4.3.2	F	The subsystem weight shall not exceed TBD kg. (Sufficient detail into the hardware required to determine weight estimates.)	NC
3.2.4.1-2	H	The surface finish shall be chemical agent-resistant in accordance with MIL-C-46168 (effect on camera lens).	NP
3.2.4.2.4-1	H	Following the application of primary power, the system shall be fully mission capable within 15 min following a time period when the system has remained in an unpowered state for at least 4 h at a temperature of -46°C (-51°F) (effect on camera).	ER
3.2.4.2.4-2	H	After a conditioning period of at least 24 h at a temperature of -46°C (-51°F), the system shall be capable of being fully mission ready within 60 min (effect on camera).	ER
3.2.6.1.1.1	H	Climatic temperature ranges between -46° and +49°C (-51° and +120°F). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	ER

\* These refer to AFAS specification paragraphs.

\*\*P = Performance, F = Form Factor, H = Hardening, M = Maintenance, R = Reliability, and S = Safety.

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.1.1.11	H	Salt fog exposure for periods up to 48 h. For test purposes, the salt fog solution shall be 5% by weight of sodium chloride in 95% by weight distilled water. The temperature in the exposure zone shall be maintained between 32° and 35°C (87.6° and 95.0°F). Fog density shall be approximately 3 L (0.79 g) of salt solution per 0.3 m <sup>3</sup> (10.6 ft <sup>3</sup> ) of chamber volume per 24 h. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NC
3.2.6.1.1.12	H	Hailstones up to 51 mm (2 in.) in diameter. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NA
3.2.6.1.1.2	H	Solar radiation varying sinusoidally from zero to 1120 W/m <sup>2</sup> (104 W/ft <sup>2</sup> ) over 16 h of a 24-h period. During the remaining 8 h of the 24-h period, the solar radiation shall be assumed to be zero. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NC
3.2.6.1.1.3	H	Ambient relative humidity ranges from 3 to 100%. The variation shall be keyed to the ambient air temperature as specified in AR 70-38. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	ER
3.2.6.1.1.4	H	Atmospheric pressure ranges from 508 to 1080 millibar. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	ER

\* These refer to AFAS specification paragraphs.

\*\*P = Performance, F = Form Factor, H = Hardening, M = Maintenance, R = Reliability, and S = Safety.

\*\*\*NA = Not Applicable, NC = Not Considered, ER = Evaluation Required, NP = No Problem Anticipated.

### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.1.1.5	H	Surface elevations from 0 to 4500 m (0 to 14,764 ft) above mean sea level. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	ER
3.2.6.1.1.7	H	<p>Icing conditions equivalent to 13 mm (0.5 in.) of glaze with specific gravity of 0.9. The system shall withstand, without permanent damage, icing conditions as follows :</p> <ul style="list-style-type: none"> <li>• 76 mm (3.0 in.) glaze, specific gravity 0.9</li> <li>• 152 mm (6.0 in.) glaze and rime mixed, specific gravity 0.5</li> <li>• 152 mm (6.0 in.) rime near the surface increasing linearly to 508 mm (20.0 in.) at 122 m (400.2 ft) altitude, specific gravity 0.2</li> <li>• TBD ice accumulation rate.</li> </ul> <p>The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.</p>	ER
3.2.6.1.1.9	H	Wind velocities up to 102 kph (63.3 mph). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	NA
3.2.6.1.2.1	H	The system shall not be damaged and from road shock when the vehicle is operated in accordance with the DRMP.	ER
3.2.6.1.2.2	H	The system shall not be damaged from vibration when operated in accordance with the system DRMP.	ER
3.2.6.1.2.3	H	The system shall not be damaged from gun firing shock or overpressure in accordance with the criteria specified in MIL-STD-1474.	ER

\* These refer to AFAS specification paragraphs.

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\*\*\*NA = Not Applicable, NC = Not Considered, ER = Evaluation Required, NP = No Problem Anticipated.

### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.1.2.4	H	<p>The system shall not incur permanent damage from exposure to the indirect lightning fields specified below for a lightning strike 10 m (32.8 ft) or more from the system.</p> <p>Radiated fields from nearby lightning:</p> <p>Magnetic field rate of change <math>3.2 \times 10^9</math> A/m/s  Electric field rate of change <math>1.3 \times 10^{12}</math> V/m/s  Maximum electric field <math>3.0 \times 10^6</math> V/m</p>	ER
3.2.6.2.1.1	H	Storage ambient air temperature. Same as 3.2.6.1.1.1 except that the maximum ambient air temperature shall be 71°C (160°F). The combat loaded system shall not incur permanent damage from exposure to the nonoperating environment specified above. Following exposure, the combat loaded system shall be capable of performing as specified by 3.2.1 (and all subparagraphs). During exposure, the system shall be in a storage or transport configuration. For transport and storage not exceeding a 90-d duration, the system shall withstand the environment with no preservation preparation. For durations exceeding 90 d, preservation protection is optional.	ER
3.2.6.2.1.2	H	Storage humidity. Ambient relative humidity ranges from 3 to 100%. The variation shall be keyed to the ambient air temperature as specified in AR 70-38. The combat loaded system shall not incur permanent damage from exposure to the nonoperating environment specified above. Following exposure, the combat loaded system shall be capable of performing as specified by 3.2.1 (and all subparagraphs). During exposure, the system shall be in a storage or transport configuration. For transport and storage not exceeding a 90-d duration, the system shall withstand the environment with no preservation preparation. For durations exceeding 90 d, preservation protection is optional.	ER
3.2.6.2.1.3	H	Transport elevation. A minimum ambient pressure of 100 millibar corresponding to failure [at 15,000 m (49,215 ft) altitude] of the air transportation system cabin pressurization equipment while the system is in transportation configuration. The combat loaded system shall not incur permanent damage from exposure to the nonoperating environment specified above. Following exposure, the combat loaded system shall be capable of performing as specified by 3.2.1 (and all subparagraphs). During exposure, the system shall be in a storage or transport configuration. For transport and storage not exceeding a 90-d duration, the system shall withstand the environment with no preservation preparation. For durations exceeding 90 d, preservation protection is optional.	ER

\* These refer to AFAS specification paragraphs.

\*\*P = Performance, F = Form Factor, H = Hardening, M = Maintenance, R = Reliability, and S = Safety.

\*\*\*NA = Not Applicable, NC = Not Considered, ER = Evaluation Required, NP = No Problem Anticipated.

### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.2.1.4	H	Fungus conditions consisting of inoculation by spraying external surfaces of the system with spore suspension as defined by the "Specimen Inoculation" paragraph of MIL-F-13927, followed by exposure to ambient air temperatures between 27°C (81°F) and 34°C (93°F) at a relative humidity between 96 and 100% for a 28-d duration. The combat loaded system shall not incur permanent damage from exposure to the nonoperating environment specified above. Following exposure, the combat loaded system shall be capable of performing as specified by 3.2.1 (and all subparagraphs). During exposure, the system shall be in a storage or transport configuration. For transport and storage not exceeding a 90-d duration, the system shall withstand the environment with no preservation preparation. For durations exceeding 90 d, preservation protection is optional.	NC
3.2.6.2.2.1.1	H	Exterior surfaces and components shall be capable of being cleaned by a steam and water jet cleaning process, using a cleaner conforming to P-C-437, without incurring damage or degradation. Jet pressures shall be 724 kPa (105 psig) $\pm$ 15.9 kPa (2.3 psig) for steam and 344.7 kPa (50 psig) $\pm$ 34.6 kPa (5 psig) for water.	NC
3.2.6.2.2.1.2	H	Interior surfaces and components shall be capable of being cleaned, using a cleaner conforming to P-C-437, without incurring damage or degradation. The interior shall have sufficient drainage capacity to permit cleaning fluids to drain at a rate which facilitates cleaning, prevents harm to the system from excess fluids, and allows the system to be dried and put back online expeditiously.	NA
3.3.2	H	The system, when fully equipped with all operational subsystems, shall meet the emission and susceptibility requirements of MIL-STD-461.	NP
3.3.2.1-1	H	The system shall meet the electromagnetic compatibility requirements of MIL-E-6051.	NP
3.3.4-3	H	In addition, system electronic components shall comply with the workmanship and soldering requirements of MIL-STD-454.	NP

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text			Preliminary Assessment Status***
3.2.6.1.1.10	H	Rain intensities as specified below:			ER
		Period	Amount (in.) (mm)	Wind speed (intermittent) <sup>a</sup> (knots/kph)	The larger drop sizes tend to be associated with the greater intensities. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.
		1 min	0.45 11.4	35/63	
		5 min	1.00 25.4	35/63	
		10 min	1.50 38.1	35/63	
		1 h	5.50 139.7	35/63	
		12 h	9.50 241.3	35/63	
		<sup>a</sup> To include each of the shorter periods intensities. Raindrop sizes ranging from 0.6 to 4.0 mm (0.02 to 0.16 in.) with a median of 2.5 mm (0.10 in.).			
3.2.6.1.1.6	H	Snow conditions consisting of falling snow crystals of 0.05 to 19.8 mm diam (0.002 to 0.78 in. diam) of sufficient density to accumulate 10 cm/h (4 in./h). Snow conditions shall persist for extended durations with maximum snow loads of 98 kg/m <sup>2</sup> (20 lb/ft <sup>2</sup> ). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.			ER
3.2.6.1.1.7.1	H	Ice fog consisting of suspended ice crystals averaging 5 to 20 μ diam of sufficient density to limit visibility to 1.5 m (4.9 ft). Susceptibility of electro-optical systems to ice fog shall be minimized. Ice fog generated by the system's engine exhaust shall not interfere with electro-optical equipment. The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.			ER

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.6.1.1.8	H	Sand and dust. Particle concentrations of $1.06 \text{ g/m}^3$ ( $6.61 \times 10^{-5} \text{ lb/ft}^3$ ) with wind speeds up to 18 m/s (59 ft/s) at a height of 3 m (10 ft). Particle sizes shall range from less than $74 \text{ }\mu\text{m}$ diam ( $2.91 \times 10^{-3} \text{ in. diam}$ ) to $1000 \text{ }\mu\text{m}$ ( $3.94 \times 10^{-2} \text{ in.}$ ) with the bulk of the particles ranging from size to $74$ to $35 \text{ }\mu\text{m}$ ( $2.91 \times 10^{-3}$ to $1.378 \times 10^{-2} \text{ in.}$ ). The combat loaded system shall be capable of performing as specified in 3.2.1 (and all subparagraphs) following exposure to the environmental condition specified above. It must also, where practicable, be capable of performing as specified in 3.2.1 (and all subparagraphs) during exposure to the environmental condition specified above.	ER
3.2.5.2.1	M	The system MTTR shall not exceed 1.00 clock h.	NC
3.2.5.2.2.1	M	The MR for unit maintenance shall not exceed 0.168 total MMH/OH.	NC
3.2.5.2.3	M	Total system shall not require PMCS (Preventive Maintenance Checks and Services).	NC
3.2.5.2.4-2	M	Any item requiring replacement at the unit level must be removable, replaceable, and adjustable in less than 1 h.	NC
3.2.5.2.5-1	M	The system shall provide a means for routinely inspecting, testing, and cleaning subsystems without removal of major assemblies.	NC
3.2.5.2.5-2	M	Accessibility shall also be provided at the Line Replaceable Unit (LRU) and Shop Replaceable Unit (SRU) levels for ease of functional and diagnostic testing and repair by the Direct Support, General Support, and Depot Maintenance.	NC
3.2.5.2.5-3	M	MIL-STD-1472 and DOD-HDBK-743A shall be used in providing access for maintenance.	NC
3.2.5.2.9.1-1	M	The system shall use embedded diagnostics/prognostics and BIT/BITE to isolate mission critical faults to at least the LRU level with a success probability of 0.95 (of faults designed for isolation and detection) at a 0.90 confidence level. (Embedded capability to fault isolate LRUs must be examined at the time of design. The recommended approach shall be part of the final recommendation).	NC
3.2.5.2.9.1-2	M	The ability to fault isolate to the SRU is desired.	NC

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.2.5.2.9-1	M	Design For Testability (DFT) shall be employed to provide the optimum diagnostic and prognostic capability considering varying degrees of Built-in Test/Built-in Test Equipment (BIT/BITE) and Test Measurement Diagnostic Equipment (TMDE).	NC
3.2.5.2.9-2	M	The DFT implementation shall identify and integrate all testability design tasks necessary to meet maintainability requirements at all levels of maintenance.	NC
3.3.1.2-1	M	Parts which are in current production and available, as indicated by qualified parts lists, shall be used whenever possible.	NC
3.3.1.2-2	M	Selection of qualified parts shall be compatible with requirements specified herein. Part selection shall be performed in accordance with MIL-STD-970.	NC
3.3.1.2-3	M	The number of unique parts shall be minimized.	NC
3.3.1.3	M	Components, assemblies, subsystems, and computer hardware and software shall be common with the FARV to the maximum feasible, cost-effective extent.	NC
3.3.1.5	M	The system shall be designed in accordance with the "hard metric" approach in MIL-STD-1476 to the maximum extent practicable.	NC
3.3.5-1	M	Components, major parts, and assemblies within the system shall be interchangeable to the maximum extent practicable.	NC
3.3.5-2	M	Standard components, parts, tools, fasteners, and test equipment shall be used to the maximum extent practicable.	NC
3.3.6.6.2-1	M	The system shall provide positive means to prevent the inadvertent mismatching of fittings, couplings, mechanical linkages, and electrical connections.	NC
3.3.7.1.1	M	The system shall be operable and maintainable by crew members while wearing Mission Oriented Protective Posture (MOPP) 4 and other environmental (e.g., Arctic) protective clothing.	NC

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.5.1.2-1	M	To the maximum extent practicable, unit maintenance shall be accomplished using only common tools and general-purpose test equipment already in the Army inventory.	NC
3.5.1.2-2	M	Special tools and support equipment shall be kept to a minimum.	NC
3.5.1-1	M	The system shall be supportable by the maintenance structure in use by the Army at the time of fielding.	NC
3.5.1-2	M	This system is expected to use the four-level maintenance concept consisting of Unit, Direct Support, General Support, and Depot Level Maintenance which are defined in 6.3.	NC
3.5.1-3	M	Maintenance shall be characterized by quick-turnaround repair.	NC
3.7.3.2.8.3.1	M	This capability shall include an integrated diagnostics and prognostics capability consistent with the system BIT/BITE requirement specified in 3.2.5.2.9.1.	NC
3.6.2.3-4	NA	The embedded training capability shall impose minimum weight and space claims upon the system.	NC
3.6.2.3-5	NA	The embedded training capability shall use reconfigured tactical systems to the maximum extent possible.	NC
3.2.5.1.1	R	The system MTBF1 shall not be less than TBD h (to be demonstrated as a point estimate) when the system is employed in accordance with the Design Reference Mission Profile (DRMP).	NC
3.2.5.1.2	R	The system MTBF2 shall not be less than TBD h (to be demonstrated as a point estimate) when the system is employed in accordance with the system DRMP.	NC
3.2.5.1.3	R	The MTBF3 shall not be less than TBD h (to be demonstrated as a point estimate) when the system is employed in accordance with the DRMP.	NC
3.2.5.3	R	The system Operational Availability (Ao) shall be at least [TBD].	NC

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.3.1.1-1	S	No material, which during any phase of the system life cycle emits toxic or carcinogenic gases, vapors, fumes, aerosols, or particles in excess of OSHA established threshold values, shall be used in the system.	NC
3.3.1.1-2	S	Radioactive materials shall not be used.	NA
3.3.1.4-1	S	Design and construction of the system shall be in compliance with applicable federal, state, and local environmental laws and regulations.	NC
3.3.1.4-2	S	The use of hazardous and environmentally unacceptable materials shall be eliminated or reduced to an acceptable compliance level.	NC
3.3.6.1.1	S	Operation, test, handling, maintenance, and storage of system hardware and software shall not present a hazard to the crew when operated within specified operational environments and limits.	NA
3.3.6.1.4.3	S	System fires shall not introduce toxic products into the crew compartment in concentrations that exceed OSHA established limits.	NC
3.3.6.1-2	S	The system shall not present any uncontrolled safety or health hazard to personnel.	NC
3.3.6.2.1	S	The system software shall not allow entries by the crew to cause a hazardous situation.	NC
3.3.6.2.2	S	The system software shall enable the crew to manually override automatic responses to equipment malfunction/out-of-limit operation in the event of an emergency.	NC
3.3.6.4.1-1	S	The use of flammable materials shall be minimized.	NC
3.3.6.4.1-2	S	Components containing flammable materials, fluids, or gases shall minimize the possibility of leaks and spills.	NC
3.3.6.4.3	S	The combination of assembled components and materials or substances shall not be a source of unintended ignition and shall not support unintended combustion.	NC

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### Crusader Automated Docking System Requirements (continued)

Paragraph*	Group**	Requirement Text	Preliminary Assessment Status***
3.3.6.6.1.2	S	Safeguards shall be specified to prevent inadvertent contact with, or entrapment of, body parts or clothing in moving parts, hatches, or doors.	NC

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**APPENDIX B**  
**DATA ON LABORATORY ENVIRONMENTAL TESTING**

**Table B.1. Baseline**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	0.03	0.023	-0.04	0.08	0.12
Y position	1.62	0.032	1.53	1.73	0.20
Z position	349.60	0.245	349.30	350.17	0.87
Roll	0.03	0.015	-0.01	0.06	0.07
Pitch	-0.08	0.053	-0.25	0.12	0.37
Yaw	-0.02	0.034	-0.13	0.06	0.19

**Table B.2. Light rain**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	0.04	0.046	-0.12	0.11	0.23
Y position	1.67	0.073	1.54	1.82	0.28
Z position	350.11	0.415	349.38	351.06	1.68
Roll	0.02	0.025	-0.04	0.05	0.09
Pitch	-0.07	0.081	-0.20	0.15	0.35
Yaw	-0.02	0.055	-0.09	0.16	0.25

**Table B.3. Fog**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	-1.24	0.26	-1.90	-0.65	1.25
Y position	1.33	0.24	0.92	1.68	0.76
Z position	351.77	1.79	349.16	355.17	6.01
Roll	-0.01	0.05	-0.12	0.07	0.19
Pitch	-0.25	0.21	-0.63	0.10	0.73
Yaw	-0.17	0.31	-0.78	0.42	1.20

**Table B.4. Droplets on lens**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	-0.91	0.052	-1.00	-0.81	0.19
Y position	2.21	0.107	1.92	2.39	0.47
Z position	351.09	0.365	350.36	351.74	1.38
Roll	0.00	0.065	-0.18	0.14	0.32
Pitch	0.74	0.182	0.30	1.08	0.78
Yaw	-0.30	0.092	-0.50	-0.05	0.45

**Table B.5. Night fog**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	-1.16	0.064	-1.30	-0.98	0.32
Y position	1.75	0.135	1.32	1.93	0.61
Z position	352.12	1.450	349.46	354.52	5.06
Roll	-0.02	0.040	-0.15	0.05	0.20
Pitch	-0.12	0.149	-0.60	0.16	0.76
Yaw	-0.35	0.207	-0.73	-0.02	0.71

**Table B.6. Lateral vibration**

Parameter (mm)	Mean	Standard deviation	Min	Max	Range
X position	-1.55	0.222	-2.05	-1.25	0.80
Y position	1.60	0.124	1.32	1.86	0.54
Z position	349.92	0.359	349.17	350.66	1.49
Roll	0.00	0.027	-0.05	0.05	0.10
Pitch	-0.09	0.050	-0.18	0.04	0.22
Yaw	-0.16	0.053	-0.27	-0.04	0.23



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