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Feasibility Report: Autonomous Docking for the Modular Artillery Ammunition Delivery System

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FEASIBILITY REPORT: AUTONOMOUS DOCKING FOR THE MODULAR ARTILLERY AMMUNITION DELIVERY SYSTEM

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ABSTRACT

The U.S. Army is planning the next generation of battlefield artillery vehicles. The new vehicles are the Advanced Field Artillery System (AFAS). The AFAS is self-propelled and can be deployed in rugged terrain. An additional vehicle is also planned to replenish the AFAS ammunition supply in the field. The Future Armored Resupply Vehicle (FARV) is envisioned to have a robotic resupply arm that can attach to a special docking port on the AFAS. In this configuration, ammunition can be transferred from the FARV to the AFAS through a motorized conveyer inside the resupply boom.

The resupply operation is greatly dependent upon the skill of the boom operator to manipulate the boom into docking position. Previous experiments have shown that computer-assisted or autonomous docking can improve the ability of the boom operator to dock safely and quickly.

A feasibility study of robotic guidance and machine vision technology was conducted at Oak Ridge National Laboratory to determine the degree to which autonomous docking is practical given the present state of technology and its direction for the future. The study was divided into three topics: a literature search, a survey of commercial systems, and a review of industrial applications.

A search in the open literature was done to identify and analyze research efforts in robotic guidance and position determination within the last 15 years. More than 250 references in autonomous docking, robotic guidance, camera calibration, 3-D imaging, and object tracking are summarized or cited. The study investigated a variety of image acquisition sensors that could be used to implement autonomous docking, including video cameras, laser range finders, ultrasonic sensors, and radar. Commercial systems for object location and tracking are beginning to appear on the market. A telephone survey of equipment suppliers was done to assess the capabilities of available hardware. Manufacturers and vendors of robotic and machine vision equipment were interviewed to determine if a commercial, off-the-shelf solution existed. A review of published articles, manufacturer's publications, and special interest groups was done to locate industrial examples of autonomous guidance in practice.

One technical challenge common to all autodocking techniques is making the design robust to the harsh environment in the field. The sensors must resist shock, temperature extremes, dust, mud, and other environmental hazards.

Based on the information gathered in this study, the recommended configuration is a single video camera, mounted on the end of the boom, along with a known, unique target, mounted on or near the docking port. The target consists of either a set of easily identifiable points or simple geometric patterns such as circles.

1. EXECUTIVE SUMMARY

1.1 BACKGROUND

The U.S. Army is planning the Advanced Field Artillery System (AFAS), which will be the next generation of battlefield artillery. The new AFAS will be self-propelled and capable of rapid deployment even in rugged terrain. To increase the availability of the AFAS for its mission, a Future Armored Resupply Vehicle (FARV) is also being planned. The role of the FARV is to replenish the AFAS ammunition supply in the field.

The FARV is also expected to be self-propelled and equipped with a robotic resupply arm or boom that can latch onto a special docking port on the AFAS. In this configuration, ammunition can be transferred from the FARV to the AFAS through a motorized conveyer inside the resupply boom. The boom can be guided into the docked position by the FARV crew. The crew can remain inside their respective vehicles during the resupply operation. This design allows the AFAS to be resupplied quickly and with increased safety for the crew.

1.2 NEED FOR AUTONOMOUS DOCKING

The success of a manual docking operation is crucially dependent on the skill of the boom operator. The operator must manipulate the axis movement controls to perform the following operations: (1) locate the docking port on the AFAS, (2) maneuver the boom into the proper alignment with the port, (3) extend the boom forward until it contacts the port and locks into position, (4) indicate that ammunition transfer can begin, and (5) retract the boom back into the stowed position for transport.

If the resupply operation is controlled from inside the vehicle, the operator will need an external sensor such as a video camera to locate the docking port and to monitor the position of the boom in relation to the port. Previous experience has shown that the operator must possess considerable skill to dock safely and avoid possible damage to the boom. The boom operators will likely need specialized training to become proficient in docking. Of particular importance is judging the distance from the tip of the boom to the docking port. Depth perception is not well developed in normal vision and is made more difficult when using a 2-D image from a video camera.

An apparatus is needed that can assist the operator in maneuvering the FARV boom to the AFAS docking port. In this report, such an apparatus is referred to as an autonomous docking system (ADS). The primary purpose of the ADS is to determine the pose of the docking port. The pose consists of six parameters: the x, y, and z position in 3-D space and the roll, pitch, and yaw orientation about the coordinate frame of the port. The system could be designed to have several modes of operation:

1. Surveillance mode with the ADS system inactive and the operator guiding the boom using the ADS video camera to monitor the outside field of view.
2. Supervisory mode, where the ADS determines the position and distance to the destination. The range and position of the port are displayed, but the operator remains in control of boom movement.
3. Semiautonomous mode, where the ADS advances the boom while the operator controls the boom's lateral position.

4. Autonomous mode, with the ADS controlling all boom movement without intervention by the operator. The autonomous mode of operation is also known as "autodocking."

1.3 AUTODOCKING TECHNOLOGY ASSESSMENT

A study of robotic guidance and machine vision technology was conducted to determine the degree to which autonomous docking is practical given the present state of technology and its direction for the future. The study attempted to answer the following questions:

1. Are there any existing applications of autonomous guidance in industry?
2. Is the hardware needed to implement autonomous guidance currently available?
3. Are the algorithms and techniques sufficiently mature for field use?

To answer these questions, three investigations were pursued: a literature search, a survey of commercial systems, and a review of industrial applications. The search in the open literature was done to identify and analyze research efforts in robotic guidance within the last 15 years. The search concentrated on topics of autonomous docking, robotic guidance, camera calibration, 3-D imaging, and object tracking. Relevant articles were collected through topical searches in the engineering data bases of technical libraries. A telephone survey of equipment suppliers was done to assess the capabilities of available hardware. Manufacturers and vendors of robotic and machine vision equipment were surveyed to determine if a commercial, off-the-shelf solution existed. A review of published articles, manufacturer's publications, and special interest groups was done to locate industrial examples of autonomous guidance in practice.

1.3.1 Literature Search

The study reviewed published literature relating to robot guidance and position determination methods. Over 200 relevant articles were identified and examined. These articles describe the theoretical techniques along with the results of laboratory experiments applying these methods. The applications discussed are for research programs or for prototype development in the general areas of robot navigation, camera calibration, and tracking. The space program is the only application area found to be directly concerned with autonomous docking.

The study found a large number of position determination methods that could be applied to autonomous docking for the FARV. The methods varied in the type and location of the sensor, source of illumination, the object on which the pose is calculated, motion of the robot or object, and techniques of estimating the position uncertainty to improve the robustness of the results.

1.3.2 Survey of Commercial Systems

Commercial systems for object location and tracking are beginning to appear on the market. The survey analyzed these systems to determine if a complete autodocking system could be purchased. The anticipated functions of the FARV autodocking task were matched with similar industrial activities such as robotic bin-picking, pose determination, object location, and 3-D scanning. All known suppliers of industrial robotic and machine vision equipment were interviewed by telephone and asked to recommend equipment to perform any of the needed functions.

There are no commercial products specifically intended for FARV autodocking; however, several systems were found that could be adapted for use in this application. One system in particular was originally developed for semiautonomous operation on the robotic arm of the space station Freedom. It can passively locate a special target in a video image and determine the position and orientation of the target. The product is in the final stages of development and is currently available.

1.3.3 Review of Industrial Applications

One guideline used to gauge the practicality of autonomous docking was the number of similar applications currently in use and the availability of off-the-shelf hardware. The study found no instance where true autonomous guidance is routinely used in an industrial environment. However, given the high potential benefit of robotics in industry, many experts believe that autonomous guidance will be common within 5 years. The study found several robotic vision systems for industrial applications under development to support that forecast.

1.4 CONCLUSIONS

The study investigated a variety of image acquisition sensors that could be used to implement autonomous docking, including video cameras, laser range finders, ultrasonic sensors, and radar. The configurations that use these sensors are divided into two categories, active and passive modes. In the active mode, one element emits energy that is detected and measured by another element of the configuration. An example of an active mode configuration is an ultrasonic system that emits acoustic pulses that are used to identify the target and determine its position and orientation. The emitter can be positioned on either the "chase" vehicle or the "target" vehicle, depending on the particular design. A passive mode configuration does not require an active element; instead, it exploits naturally occurring energy sources such as the sun. The only passive configuration found by this study was the video camera when using available light.

Active configurations are conceptually feasible but have several significant disadvantages. Active designs typically require that the target vehicle cooperate in the docking process by signaling its presence to the chase vehicle. Unless the active element runs continuously during docking, then the two vehicles must have a communications link to synchronize the process. This increases the complexity for all target vehicles because of the additional components.

A camera-based system is the preferred choice for applications requiring passive operation. The overwhelming majority of reported cases used one or more video cameras in their guidance systems. In most cases, the camera was selected because of its inherent simplicity, low cost, and widespread availability. In addition, the video output from a camera is readily interpreted by humans, making it directly compatible with manual docking procedures. It is worthwhile to note that the National Aeronautics and Space Administration (NASA), the agency with the longest history in autonomous docking, has concentrated its efforts on vision-based autodocking systems.

Some pose determination methods have been researched more extensively with additional experimental testing and more efficient algorithms. From these, preferred approaches to autonomous docking have been identified which can be further developed with less risk and uncertainty. Based on the information gathered in this study, the recommended configuration is a single video camera, mounted on the end of the boom, along with a known, unique target, mounted on or near the docking port. The target consists of either a set of easily identifiable points or simple geometric patterns such as circles. The camera is used to form an image of the area surrounding the docking port, including the unique target. An image processing system locates the target in the image and calculates the relative pose between the boom and the port. As the boom moves toward the port, the port occupies a larger percentage of the image. This improves the accuracy of the pose calculation for closer ranges.

One technical challenge common to all autodocking techniques is making the design robust to the harsh environment in the field. The sensors must resist shock, temperature extremes, dust, mud, and other environmental hazards. Each sensor is vulnerable to one or more of these conditions but could be protected by environmental enclosures.

Even though it was first demonstrated over 25 years ago, autonomous docking technology is still in its infancy. The slow growth is partially attributable to the lack of a widespread demand to drive the development of new technology. Equipment development thus far has been primarily for space applications. As robotic manipulators expand into industrial applications, the demand for vision-based guidance support should continue to grow. An increasing demand for improved vision in robots bodes well for autonomous docking.

The forecast for autonomous docking of the FARV is favorable. Several techniques for autonomous robotic guidance have been successfully demonstrated under controlled conditions. The hardware needed to implement an autodocking system on the FARV is available but largely unproven outside the laboratory. Any unresolved performance issues should be addressed with field tests using a working prototype. Autonomous docking is a leading edge technology but is sufficiently mature that it should be considered feasible.

2. BACKGROUND

This report is a survey of autonomous rendezvous and docking techniques as applied to the Future Armored Resupply Vehicle (FARV). The goal of this study is to assess the present state of technology to determine if a computer can be used to either assist the operator in the docking operation or to relieve the operator from primary responsibility for docking. The latter option is called autonomous docking, or autodocking.

An autodocking system is desired to assist the operator in guiding the resupply boom to a docking port on the Advanced Field Artillery System (AFAS). The degree of assistance provided by the autodocking system could range from true autonomous operation, independently locating the port and docking without operator intervention, to merely giving the operator a robot's eye view of the outside world. A completely autonomous system would relieve the operator from the responsibility of driving the boom to its destination.

2.1 FARV PROGRAM

The U.S. Army has initiated a program to develop the next generation of heavy field artillery. The AFAS will be an armored vehicle equipped with a large-bore gun. The AFAS is self-propelled and tracked, giving it exceptional mobility in rugged terrain. The ammunition supply vehicle must be equally mobile to support the mission objectives of the AFAS.

The FARV is a concurrent program to develop a vehicle to resupply the AFAS with ammunition in the field. The FARV is presently envisioned to be a self-propelled carrier that can transport ammunition and propellant to the AFAS units. The FARV can be deployed near the battlefield to rendezvous with the AFAS units for resupply. The FARV can position itself close to the AFAS, then extend an internal, robotic transfer boom to a matching receiver or docking port on the AFAS. After connecting to the AFAS docking port, ammunition rounds can be loaded onto the AFAS through a mechanized conveyer in the FARV resupply boom.

The ammunition transfer boom of the FARV is being developed as part of the Modular Artillery Ammunition Delivery System (MAADS) program. The boom is a six degree-of-freedom robotic arm with a self-contained conveyer to move artillery rounds from one vehicle to another. The end effector may have a self-latching clamp to secure the boom to the AFAS docking port for reloading. The FARV crew could perform the docking procedure by guiding the transfer boom into position and engaging the AFAS port.

An important principle of the FARV concept is to minimize the crew's exposure to nuclear, biological, or chemical hazards. The mechanized resupply boom eliminates the need for a ground crew to manually transfer artillery rounds between the FARV and the AFAS. This allows the crew to remain inside the armored vehicle during reloading operations. The FARV transfer method is also faster than transferring shells manually, reducing the time spent for resupply operations.

2.2 NEED FOR AUTODOCKING

The process of remotely docking two vehicles is an extremely complex task. Experiments at the National Aeronautics and Space Administration (NASA) have shown a wide variation in performance from mission to mission and between pilots.[1] Even partial automation of the docking operation would improve performance and give more predictable results. Digital simulations at the Marshall Space Flight Center in 1981 indicated that the performance of an autonomous docking system equalled or exceeded that of a trained pilot.[2]

A common method of remotely guiding a robotic boom in an unstructured environment is teleoperation. In teleoperation, a human operator manipulates the controls to extend the robotic boom to the desired location. The teleoperator is usually assisted by one or more video cameras to view the remote environment. The operator uses the cameras for visual feedback when positioning the boom. A significant difficulty in teleoperation is the lack of depth cues from the video camera, which, like the eye, generates a 2-D projection of the natural 3-D scene. As a result of this projection, the position and orientation of objects are often ambiguous because of the lack of depth cues. This makes it difficult to judge precisely how far away an object is. Normally, our brains use a set of external depth cues to compensate for the lack of depth perception. The process is so well-practiced that we are not aware of it.

Some important depth cues are size, obscuration, motion parallax, and binocular parallax.[3] The relative size of an object suggests the distance, with larger objects appearing to be closer than smaller objects. When one object lies behind another opaque object, the further object is obscured from view by the near object. The shadow and texture content of the two objects helps us to gauge their separation. Some ambiguities are resolved by motion parallax. When the head is moved slightly to change the viewpoint, the relative motion of scene objects indicates the distance. Assuming the object itself is stationary, near objects will have greater motion than far objects when the head is moved laterally. In biological sight, an object is imaged onto the retina of each eye. The object distance is determined by comparing the two images in a process called binocular parallax, the distance being proportional to the amount of shift required to bring the two objects into alignment. An additional task of the brain is to identify the same object in both images.

A system to improve the operator's depth perception would be of great benefit in docking operations. An automatic system to locate the docking port, determine its pose, and supply the pose coordinates to the boom control system is defined here as the autonomous docking system. The pose of an object consists of its location on the x, y, and z reference axes in 3-D space; and the orientation is its rotation or roll, pitch, and yaw about those axes.

The autodocking system by necessity must be tightly coupled to the control system of the robotic boom. The sensor must be mounted near the boom's end effector to provide the proper viewing perspective for either manual or autonomous operation. In autonomous operation, the control system must be capable of accepting new position coordinates from either the operator or the autodocking system.

2.3 POSE DETERMINATION PROBLEM

The problem of autodocking pose determination is shown in Fig. 1, where the separate 3-D reference frame for each of the four major components is shown. The desired result is the coordinate transformation between the docking port and the boom end. This transformation is denoted by a 4 × 4 matrix $\mathbf{T}_{BP}$ in the figure.

Transformation $\mathbf{T}_{BP}$ cannot be calculated directly because the parameters used in the calculation are obtained from the pose determination sensor. Although the sensor is typically mounted near the boom end, its coordinate frame is independent of the boom. Therefore, $\mathbf{T}_{BP}$ must be calculated in two steps. First the transformation between the sensor and the port $\mathbf{T}_{SP}$ is calculated by means of a pose determination method. This transformation is given by

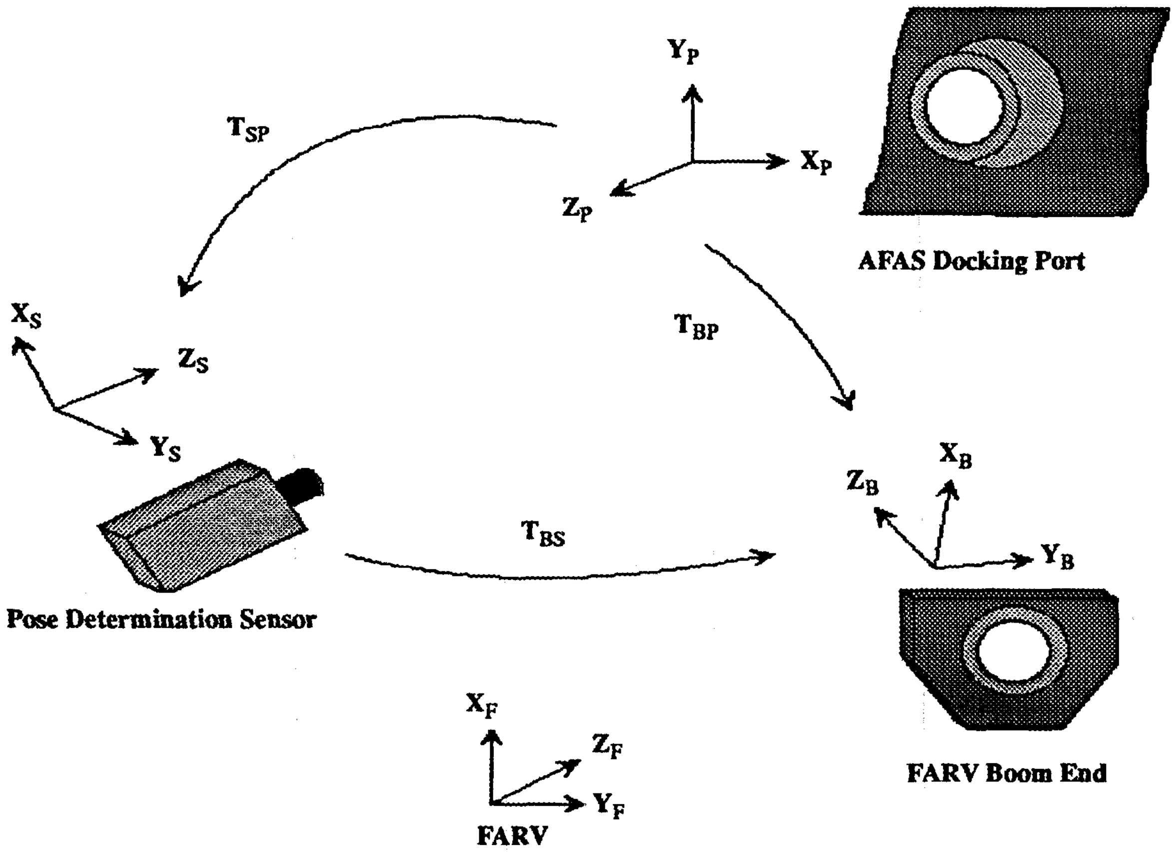

Fig. 1. Illustration of the coordinate frames required in autodocking.

$$\mathbf{x}_S = \mathrm{T}_{SP}\mathbf{x}_P \ ,$$

where $\mathbf{x}_S$ and **x**P are 4-element vectors giving the coordinates of a point with respect to the sensor reference frame **S** and the port frame **P**, respectively, that is, $\mathbf{x}_S = [x_S\ y_S\ z_S\ 1]$T. T_{SP} is the 4×4 transformation matrix between the **P** and **S** frames.

Secondly, the transformation between the sensor frame and the boom end frame must be applied.

$$\mathbf{x}_B = \mathrm{T}_{BS}\mathbf{x}_S \ ,$$

where $\mathbf{x}_B$ is the coordinate vector with respect to frame **B** and T_{BS} is the transformation matrix between the **S** and **B** frames. With the sensor mounted on the boom end, $\mathbf{T}_{BS}$ is fixed and can be predetermined during an off-line calibration and then stored. Substituting for $\mathbf{x}_S$ above gives

$$\mathbf{x}_B = \mathrm{T}_{BS}\mathrm{T}_{SP}\mathbf{x}_P \ .$$

From this equation, it can be seen that a point on the boom $\mathbf{x}_B$ is related to a point on the port $\mathbf{x}_P$ by $T_{BS}T_{SP}$, and therefore T_{BP} must be

$$T_{BP} = T_{BS}T_{SP} .$$

Applying T_{BP} to a point referenced to the docking port gives the 3-D coordinates with respect to the boom end. The six pose parameters of relative position and orientation of the docking port to the boom end can then be calculated from T_{BP}.

2.4 RENDEZVOUS AND PARKING PHASE

The FARV may have to travel many miles from its base to meet with the AFAS. This part of the operation is called the rendezvous phase. In the rendezvous phase, the FARV is driven to the designated location. The parking phase occurs after the FARV is within sight of the AFAS. In the parking phase, the driver maneuvers the FARV so that the AFAS is within reach of the robotic boom.

Once the boom is extended, any abrupt movement of the FARV could damage the boom, either from excessive loading or from possible collisions with nearby obstacles. If the AFAS is beyond reach of the boom, the boom must be retracted and stowed while the FARV is repositioned. To complete the resupply operations in the minimum amount of time, the AFAS should be within reach of the boom before starting the docking procedure.

It would be beneficial for the driver to have a coarse position monitor to confirm that the AFAS is within reach of the resupply boom. The coarse position monitor should operate independently from the autodocking system because the autodocking sensor will probably be mounted on the boom, which must be retracted and stowed during transit. This reduces the availability of the autodocking camera for coarse position monitoring.

Some possible methods of coarse position measurement include: (1) point sensors mounted on the exterior of the vehicle, (2) a separate video camera, or (3) a special optical sight glass. Point sensors such as ultrasonic sensors to measure range could be mounted on the front of the FARV. The measured separation distance between the FARV and the AFAS could be displayed visually on a dashboard-mounted digital range indicator. When the range meter indicated that the AFAS was within an acceptable distance, the FARV could be parked.

A separate video camera could be used to help the driver position the FARV by monitoring the location of the AFAS. A cathode ray tube (CRT) could be equipped with a set of video field markers to indicate the range from the relative size of the AFAS image. When the AFAS was within acceptable range, the image of the AFAS would fit within the field markers.

An optical sight tube could be used to give a viewing port to the front of the FARV. The optical properties of the sight tube, such as field of view, could be designed to match those of the autodocking system. The normal operational envelope could be shown with fiducial marks in the image. The driver could then look through the sight tube to verify that the AFAS port was within the appropriate markers.

The rendezvous and parking phases are both important operations leading up to docking. Docking, whether done manually or automatically, cannot begin until the FARV has been parked within docking range. The FARV may require additional components to monitor the rendezvous and parking operations. In this report, rendezvous and parking issues are acknowledged but not included in the assessment of the autonomous docking system.

2.5 ASSUMPTIONS

The analysis of the autonomous docking system is made before the design of either vehicle has been finalized. Consequently, many assumptions must be made regarding the specifications and operation of the AFAS, FARV, and the robotic boom.

2.5.1 FARV Position

The operating assumption is that the FARV will be parked within the effective envelope of the boom arm before beginning the docking sequence.

2.5.2 Resupply Boom

Length	8 ft (fully extended)
Rotation	10° arc about any joint
Orientation	Vertical

2.5.3 Docking Port

Geometry	Circular
Diameter	8.5 in.
Alignment tolerance	0.3 in. lateral misalignment, 3° of axial rotation

2.5.4 Accuracy

The positional accuracy and resolution requirements for the autodocking sensor have not been determined.

2.5.5 Speed

The speed of the autodocking system will be determined by the complexity of the algorithmic computations and the capabilities of the hardware. Obviously, greater complexity requires more computations and either more time or higher performance hardware. The penalty for lower speed in this application is a lower rate in updating the position of the destination. This would only mean fewer updates as the boom advanced.

3. AUTODOCKING TECHNOLOGY ASSESSMENT

3.1 GENERAL OVERVIEW

A study of robotic guidance and machine vision technology was conducted to determine the degree to which autonomous docking of two land vehicles is practical given the present state of technology. Autonomous docking technology was arbitrarily broken into four stages of maturation:

1. The research stage, where conceptual ideas and theories are being investigated at the university level. This is the earliest state of technology where marketable products will be available in 5 to 10 years.
2. The development stage, where commercial companies have taken research theories and are attempting to implement them. Products in this stage of maturation can be expected on the market within 1 to 2 years.
3. The commercial stage, where products are being manufactured and are available to the general public.
4. The industrial stage, where the technology is in common practice and is well accepted.

The study concentrated on technologies that are currently available, that is, having products at least in the development stage as defined above.

Consequently, the study was divided into three main paths of investigation to gauge the technical maturation level of autonomous docking: a literature search, a survey of commercial systems, and a review of industrial applications. Technologies that were published in research journals 15 years ago would likely be mature today. Likewise, technologies that are in the research stage now and are being published are an indication of the direction for the future. The quantity of commercially available products was used as an measure of the commercial stage of technical maturation. The quantity of industrial uses of robotic guidance was used as a guide for the industrial stage of maturation.

The search in the open literature was done to identify and analyze research efforts in robotic guidance within the last 15 years. The search concentrated on topics of autonomous docking, robotic guidance, camera calibration, 3-D imaging, and object tracking. Relevant articles were collected through topical searches in the engineering data bases of technical libraries. While there are many promising developments that bode well for autonomous guidance in the future, only those technologies with published histories were pursued. Of particular interest were those cases that had verified their theories experimentally through laboratory demonstrations.

A telephone survey of equipment suppliers was done to assess the capabilities of available hardware. Manufacturers and vendors of robotic and machine vision equipment were surveyed to determine if a commercial, off-the-shelf solution existed.

A review of published articles, manufacturers' published data, and special interest groups was done to locate industrial examples of autonomous guidance in practice. A list of references used in this report is included in Sect. 6.

A detailed study of every possible autonomous docking technique is beyond the scope of this report. An attempt was made to survey the technology and to give general information on representative techniques or alternatives. The report is intended as a guide for decision-makers in evaluating if an autodocking system is realistic.

3.2 LITERATURE SEARCH

The need for a computer-assisted autonomous docking system (ADS) to improve the operator's depth perception has been shown earlier. For the desired case of totally autonomous operation, the ADS must determine the pose of the target docking port. The pose parameters are subsequently transmitted to the boom control system. In this section, a typical docking system is decomposed into its major functions. The functional model is used to separate function from implementation when comparing the alternative technologies.

Regardless of the particular technology that is implemented, the ADS must identify the target, determine the range and direction of the target, and convey that information to the control system. The control system is responsible for actually moving the resupply boom to the designated position. The ADS can be divided into four major functions: (1) form an image representing the remote environment; (2) identify and track the desired target within the image; (3) extract the position and orientation of the target from the image; and (4) interact with external devices, including the operator. The functions used in this section apply to any of the possible implementations under consideration. For example, the ADS must generate an image of the target area whether implemented with a video camera, ultrasonic sensor, laser camera, or radar. A simplified functional diagram of ADS is shown Fig. 2.

3.2.1 Image Formation

Image formation of a 3-D volume can be divided into two categories for discussion: (1) Active techniques, which require the emission of a controlled beam of energy and measurement of the returned energy. Examples of active sensors are lasers, radar, ultrasonic sensors, and contrived illumination. Contrived illumination is the use of special lighting to scan the target area. (2) Passive techniques, on the other hand, do not require an energy emanation for normal operation. The technique that uses passive sensing to acquire the image is the video camera. The camera does not require special emanations to probe the target region such as with a laser range finder. The video camera is also the most analogous to human vision, which is important if manual docking capability is also needed.

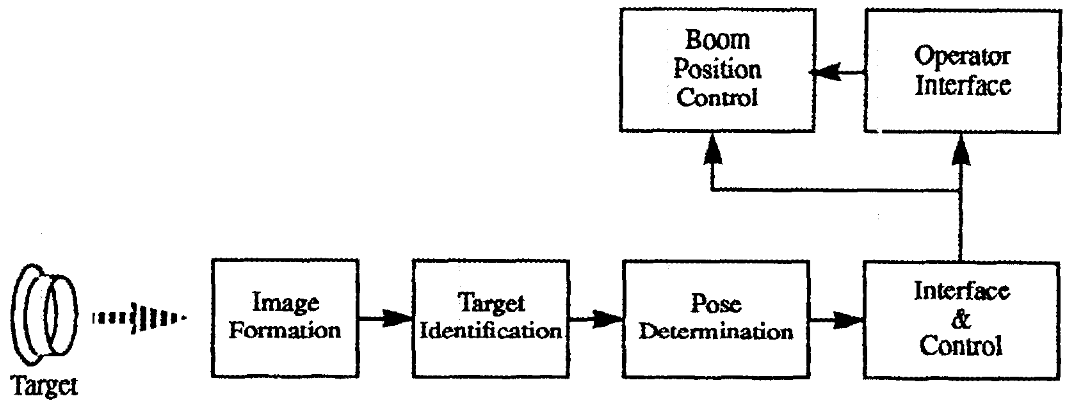

Fig. 2. Functional diagram of a typical autonomous docking system.

3.2.1.1 Video camera

Several techniques exist for obtaining 3-D range information from one or more video images. These techniques rely on knowledge of the camera parameters and the object to be imaged. For example, given the focal length of the camera and the geometry of the object, the 3-D coordinates and orientation angles of the target relative to the camera can be calculated. For some special cases, occlusion clues or texture analysis may be used to find relative dimensions in a scene.

The advantages of a single-camera system for 3-D image formation include simpler, less expensive equipment and potentially faster processing. Additionally, the video camera provides the highest level of passive sensing. A potential disadvantage to the video camera is the necessity to identify the target based solely on visual parameters. While it is a simple task, even for a small child, to distinguish a cat from a dog, it is exceedingly difficult to develop a computer program to perform the same feat.

Stereo vision was one of the earliest 3-D ranging techniques. Its use grew out of attempts to model the human vision system. To create a 3-D image with stereo vision, two cameras with identical lenses are separated by a fixed distance to emulate binocular vision. Each camera has a slightly different view of the target because of the separation. The range to the target is proportional to the displacement between similar points in the left and right images. An equivalent implementation with a single camera would be to obtain two images in succession, with the camera displaced in the horizontal or vertical direction for the second image. This is often referred to as stereo disparity.

In addition to the usual disadvantages of a single-camera system, the stereo camera system also has the added burden of image correspondence. A significant problem in determining depth information from a stereo vision system is matching corresponding points in the two images. This can occur because of nonuniformity of the image intensity, partial occlusion of the target in one image, or extreme differences in the field of view. The range calculation is more accurate if the camera separation distance is large, but the correspondence problem becomes more difficult as the likelihood of locating corresponding points also decreases.[4]

3.2.1.2 Laser range camera

Laser cameras form a range image by scanning the scene with a tightly focused amplitude-modulated infrared (ir) laser beam. The laser beam is swept across and up and down the field of view by rotating mirrors. The reflected light from the scene is detected by a receiver that measures the intensity and phase of the returned light. The range at each point in the image is calculated from the phase shift caused by the time delay of the returned light. The reflectance at each point is proportional to the intensity. Thus the laser camera simultaneously provides both a reflectance image and range image.

The advantage of a range camera is the direct mapping of distance to points in the image and the availability of the reflectance image. The disadvantages of laser cameras include generally slower frame rates because of mechanical limitations in scanning, the fragility of the mechanical scanning components, limited range accuracy, and personnel safety concerns about the laser beam.

3.2.1.3 Ultrasonic sensor

Ultrasonic range finders transmit a multifrequency chirp of acoustic energy that is reflected off an object and returned to the transducer. The distance to the object is determined from the time interval between emission of the signal and receipt of the reflected wave. The speed of sound in air, which can vary with atmospheric conditions, must be known. Even with special acoustic focusing techniques, the ultrasonic beam cannot be focused narrowly enough to produce a high-resolution range map. Ultrasonic sensors are generally used for object detection/obstacle avoidance.[4,5] Ultrasonic sensor configurations that can identify a target and determine the pose in controlled experiments have recently been reported.[6]

3.2.1.4 Electromagnetic sensor

Electromagnetic sensors such as radar transponders were used in the first autodocking exercise in space. Several approaches have been described using X-band and Ku-band radar.[7] The majority of the cited examples was intended for long-range applications such as the approach phase of space rendezvous. Radar methods used in close-range docking operations were reported to have position errors of 10 in. Radar is an active sensing method that emanates electromagnetic energy.

3.2.1.5 Contrived illumination

Range images can also be generated with a technique called structured light. A separate illuminator projects a thin bar of light across the scene. The light source is usually off-axis from a viewing camera by 45°. The bar of light extends across one dimension of the image, say, across the width. For a flat surface, the light appears as a continuous horizontal line, but for an elevated surface, this line is displaced from its reference proportional to the object height. The object height is computed from the amount of displacement. This technique is used mainly for industrial applications to determine the height of an object relative to a reference surface, such as a conveyer belt. A more complicated variation is projection of Moire fringe patterns over the field of view. Compared to the other image formation alternatives, this technique has limited utility for autonomous docking.

3.2.2 Target Identification

The task of target identification or recognition is an important part of any automated vision task. An object that is easily identified by even a small child can be difficult to characterize in an algorithmic structure so as to uniquely distinguish it from nearby objects. The algorithms used to identify and locate a target in the image are generally based on the object shape or by the edge contour.

The simplest automated target identification situation is locating an object in an uncluttered background, using controlled lighting and with the camera at a known distance. Finding this same object in a busy scene, under arbitrary lighting, at an arbitrary orientation and distance relative to the camera presents a much more challenging problem. Traditional methods attempt to control these environmental parameters in order to better isolate the object from its background.

Because shape recognition techniques require thresholding the image, they tend to be very sensitive to illumination nonuniformities, and they work best with high-contrast images.

Uncontrolled lighting can cause bright reflections from metallic surfaces or dark shadows that greatly reduce the effectiveness of thresholding and segmentation algorithms. The contour image is generated from the high-frequency components of the original image. Consequently, recognition techniques based on contours are less sensitive to illumination nonuniformity but are more susceptible to noise.[8]

In cases where it is impractical to control the illumination, special marking techniques are often used to make an object recognizably unique. Recognizable markers can be attached on or near the target as an identifying label. The labels may be reflectors or distinctive illumination patterns that are projected on the scene. The projected patterns may be emitted by the image acquisition system or by the target itself. The target can be recognized with a high degree of certainty by searching for the special marker in the image and ignoring everything else. Even if the object can be recognized naturally, the labels can often reduce the computational complexity and increase the confidence that the correct object has been identified.[9]

3.2.2.1 Identification labels

One method of uniquely identifying the target is with a spectral label. The spectral label either emits or reflects light within a narrow band of wavelengths. The wavelengths of interest are known by the target identification system. The known characteristics of the labels allows them to be isolated from an otherwise cluttered background.

Marshall Space Flight Center proposed this type of technique for autonomous rendezvous and docking of space craft. Their docking aid design used five laser diodes at 780 nm and five at 830 nm mounted on the chase vehicle. The target vehicle was equipped with three retroreflectors in a row, with the center reflector elevated 4 in. above the others. Each retroreflector had an optical bandpass filter that reflected light at 830 nm but absorbed light at 780 nm. During the docking operation, an image is first acquired when the 830-nm diodes are illuminated. The selective spectral response of the retroreflectors causes them to appear as bright objects in the resultant image. The 830-nm diodes are blanked and the 780-nm diodes are illuminated during the second image acquisition. Because the retroreflectors absorb light at this wavelength, they appear dark in the second image. The two images are very similar except for the absence of the retroreflectors in the second image. The retroreflectors were then easily isolated by subtracting the two images.[10]

Illuminators and reflectors of a specific wavelength are also used to establish correspondence points for determining disparity in stereo images.[9] Tuned-frequency lasers are sometimes used to project spots on a target to provide corresponding references for stereo imaging. Equivalently, specific-wavelength reflectors on the target can be used to solve the same correspondence problem.

In addition to keying on spectral characteristics, objects can be located by using temporal clues as well. Lights flashing at a fixed frequency or illuminated in a specific sequence can serve as markers for an object and its orientation. Martin Marietta Denver Aerospace proposed and tested a flashing light docking aid for autonomous video rendezvous and docking. This system used three lamps in a row, with the center lamp elevated. The lamps are illuminated sequentially, and their firing time is controlled by the chase vehicle over an rf (radio frequency) link. This allows the image acquisition to be synchronized with the flash rate of the lamps. The feature points in the image can be isolated because their separation in time is set by the flash rate and order of illumination.

Another docking aid design uses lamps mounted on the target. The lamps are alternately turned on and off, causing them to flash at a specific frequency. The input image is passed through a bandpass filter centered at the flash frequency, which attenuates other objects in the scene. Researchers at Oak Ridge National Laboratory (ORNL) have demonstrated such a technique using flashing ir light-emitting diodes (LEDs) to identify the target.[11] The use of independently flashing lights at varying frequencies has also been mentioned as a possible alternative to the T-shaped docking aid proposed by Martin Marietta Aerospace.[12] Another alternative technique would use colored lights and polarization filters to distinguish target labels. This method relies on the separation of the label's wavelength rather than its firing time. Red and green lamps replace the flashing lamps in the previous example. A color camera with three separate sensors allows simultaneous tracking of multiple points.[12]

Other special identifying tags may be used to indicate the location of an object. A spectral marker such as an ir ring will emit ir energy that can be detected with either an ir camera or a conventional camera equipped with an ir filter. A fiber-optic ring light could function similarly. A passive identification tag is the 2-D bar code that is mounted on the objects to be located and tracked.[13] Marking dyes that fluoresce under ultraviolet illumination have also been used in industrial vision inspection systems to rapidly locate small washers in complicated assemblies where the components may be partially occluded.[14]

3.2.2.2 Shape

Another target identification technique takes advantage of a known geometry of the target or its label. For example, circles have been shown to be easy locatable in an image with high accuracy.[15] Other proposed geometric markers mentioned in the literature include a diamond, a calibrated sphere with two large perpendicular circles drawn on the sphere's surface, and a trapezium. Some of the more unique patterns reported include a black-and-white spiral pattern and a planar target of two right triangles with the same orientation and the smaller centered inside the larger.[16,17] Combining the method of known geometric shape with the illumination, Marshall Space Flight Center has proposed a circular pattern of eight lights or reflectors that are located on a common plane on the target. An ellipse (a prospective view of the circle) is fitted to the centers of the lights, and its orientation and eccentricity are used to find relative attitude and range of the actual object.[1]

3.2.2.3 Optical correlation

Correlation techniques provide a measure of the similarity of an image or image segment with a predefined model or prototype image. The higher the similarity, the more likely that a good match exists between the two images. The similarity measurement is made on the Fourier transform of both images. An optical correlator allows this normally time-consuming operation to be performed at the speed of light. A variety of docking patterns that yield good results using optical correlation has been developed and tested. Martin Marietta Photonic Systems, the Jet Propulsion Laboratory, and Johnson Space Center have published target tracking and recognition systems utilizing optical correlation.[18–20]

3.2.2.4 Operator-defined target

A semiautonomous method of target identification relies on the operator to define the target with a mouse or other pointing device. While complete autonomy may increase efficiency and predictability in performance of the docking task, it is difficult to replace the human's versatility and capability of handling the unexpected.[1] Semiautonomous operation could be advantageous in the event of abnormal conditions or some types of equipment malfunction.

3.2.3 Parameter Measurement

This section describes published methods of noncontact position and orientation determination. These methods are generally based on single-vision cameras, stereo cameras, or on range images from laser, ultrasonic, or structured lighting devices. The articles found in the literature give theoretical techniques along with the results of laboratory experiments applying these methods. A large number of position determination methods that could potentially be applied toward autonomous docking for FARV have been found. Variations in the methods include type and location of sensor, illumination requirements, the object or scene on which the pose is calculated, the motion of the robot or object, and the modeling of uncertainty or noise in an attempt to improve the robustness of the results. Accuracy results reported are within the preliminary alignment tolerances defined for the AFAS docking port.

Remotely determining the position and orientation or pose of an object has been a subject of considerable research in the areas of photogrammetry, robotics, and computer vision. The general problem is to locate the object in three dimensions based on three-position and three-rotation coordinate parameters either relative to an observer or with respect to a fixed reference frame. Known as the exterior orientation problem in photogrammetry, this question has been addressed for photographs using a number of manual methods going back to 1879.[21] More recently, beginning in the 1960s, methods using computer vision techniques have been developed. Most measurement techniques for pose determination are based on an image and can be classified into the two major categories of point-based methods and model-based methods. Each type involves acquiring an image, either 2-D or 3-D, extracting salient features from the image, and then processing those features to determine the pose. The different techniques and applications are summarized below.

3.2.3.1 Point-based methods

Point-based methods rely on the identification and location of feature points on a target object from the 2-D image of the scene. The only physical assumption about the object is that the points are located on a rigid body. Information concerning the geometric shape is not used in calculating the pose. Coordinates of the points in a local or world reference frame may or may not be known.

Methods of this class, referred to as N-point perspective, were the first to be studied and as a result have been more extensively developed than model-based methods.[22] A perspective model is used which assumes the projection of a 3-D object onto a 2-D image plane through a pinhole camera model.[23] Both single-image and stereo methods have been reported although single-vision techniques have by far the greatest number of solutions. One reason is that point correspondence with an object from a single image is easier than determining correspondences between two images and the object, as is required in stereo. The general framework is, given N corresponding points in the object and in the image, to solve for the relative pose between the camera and the object.

The minimum N to give a finite number of solutions is 3, although up to 4 solutions are possible. Four coplanar, noncollinear points give a unique solution. Four or five noncoplanar, noncollinear points give up to 2 solutions. For N greater than five noncollinear points, the result is unique and consists of an overdetermined set that can be solved using least squares methods.[24] In general, as N increases, the accuracy of the results increases. These overdetermined solutions are used for camera calibration in which a large number of points are needed to achieve the desired accuracies and to calculate both the external and internal camera parameters.[25] Three- and four-point, coplanar targets have been directly used for pose determination.

With stereo cameras, three corresponding points on an object are sufficient to uniquely identify the relative pose of the object although uncertainty may be reduced through a larger number of points.[26] Range images, similarly, can determine pose with a minimum of three points. An advantage of 3-D range images over stereo is that the correspondence problem is not present since the three coordinates of an object point are determined directly.

Algorithms for these techniques are primarily iterative. For the three- and four-point special cases, however, closed form solutions have been demonstrated.[24,27]

3.2.3.2 Model-based methods

Model-based methods of pose determination use the geometry of the object in addition to its image in determining the pose. The object is modelled in terms of lines, curves, planar surfaces, or quadric surfaces. Some methods obtain these features from computer-aided design (CAD) models.[28] Other papers restrict or simplify the model so that the object can be described easily and the computation involved is reasonable.[29] As in point-based methods, a perspective vision model is generally assumed. Orthographic models with scaling have also been reported which simplify the computation, but the accuracy is limited at closer ranges because of the perspective approximation.[30] For this class, methods have also been developed for single-vision, stereo, and range images. From the 2-D image in single-vision techniques, which is the perspective projection of the known 3-D object, the problem is to determine the rotation and translation of the object that would give rise to the given 2-D projection. Edges and vertices must be recognized and matched with corresponding features in the object for the pose to be calculated. One important example is the calculation of the pose from the image of a circular feature (an ellipse) using a closed form method.[31] An ellipse is fit to the feature edge through minimization of an error criterion. Two solutions result from one image; so an additional feature or an additional image is required to derive the correct pose.

Methods using range images are predominately model based. The range image is 3-D rather than 2-D as with intensity images; so additional information is present for matching features to the object. Algorithms, however, are generally iterative and are based on nonlinear minimization of a cost function relating the image features with the object features.[32] Hypotheses and verification may also be performed to determine the correct pose.[33] A method has also been developed using neural networks to solve the problem with Kohonen-Nets.[34] Stereo methods, by determining the 3-D coordinates of features through matching, are similar to range image methods.[35]

Model-based techniques, by taking advantage of the inherent geometry present in the object, give more accurate results than point-based methods, given the same number of features.[24] The cost is additional computation. Many more techniques have been reported using single-intensity images along with accuracy results. Solutions have also been shown to address uncertainty and sensitivity to missing features.[36] As a result, in the applications where targets with optimum geometry may be predefined for a particular technique, model-based methods using single-vision cameras are more developed and have been shown to give more accurate results for close-range measurements.

3.3 COMMERCIAL SYSTEMS

A review of commercial vendors and manufacturers was conducted to determine if a commercial, off-the-shelf product was suitable for autonomous docking. The functions defined previously in the autodocking functional diagram were matched with common industrial applications of robotic equipment. The selected industrial applications were 3-D dimensional inspection, bin picking, robotic guidance, and target tracking. These were chosen because the underlying functionality needed for the industrial applications is similar to autodocking. Therefore, equipment designed for the industrial applications could be adapted for autodocking. The vendors were interviewed by telephone and asked to recommend equipment capable of remotely measuring the position and orientation of a designated target. They were also asked to recommend alternative methods or products that might be suitable for the selected industrial applications.

The vendors in this survey were selected from buyer's guides for the robotic and vision industry. The vendors were categorized into four groups: (1) manufacturers that develop and integrate guidance systems and proprietary software into their robotics systems; (2) manufacturers that build guidance components such as image acquisition and processing boards for a PC, VME, or Apple platform; (3) companies that manufacture sensors and discrete components such as ultrasonic transmitters; and (4) consultants and system integrators that develop custom systems for a particular application. The list of vendors was then sorted by group, with the manufacturing group having the highest priority and the consulting group the lowest. The list of the vendors contacted for this survey is given in Appendix A.

The products described here are intended to gauge the state of the art in robotic guidance. In cases where several companies have similar products or features, one product is chosen as representative of the technology. The technical information contained in this report was quoted from the manufacturer's published data sheets and has not been confirmed by the authors.

The authors attempted to contact all known suppliers of robotic, vision, or ranging equipment with offices in North America. The objective of this study was to assess the maturity level and breadth of autonomous docking technology and not to specify a particular model. It is likely that other products are available with features similar to the models mentioned in this report.

3.3.1 Guidance Systems

Kinetic Sciences, Inc. (604-822-5782), offers the Eagle Eye vision system, which determines the pose of a special 2-D bar-coded target. The system uses the bar code to identify the target within the image, and then it matches the target with a stored model to determine the position and orientation. The target size is determined by the desired operating distance. The Eagle Eye was originally developed for autonomous guidance applications aboard the NASA Space Station.

Tau Corporation (408-395-9191) has developed the Eagle/RT Real-Time Video Tracker. The Eagle uses a single camera view to estimate a known target's six degrees of freedom. This system has an option to determine the position and orientation of a solid object. The Eagle/RT requires an operator to initially designate the target on the CRT monitor. The system was developed for military applications in video tracking of aircraft and missiles.

The Imago 100 Video Target Tracker from Imago Machine Vision (613-728-9831) tracks a target using a combination of motion, contrast, size, shape, and edge contrast. The system can successfully track objects in a variety of lighting conditions and with noisy images. Because this system runs on a PC, the frame update rate will be lower than systems using high-performance workstations.

The Perceptron Co. (313-478-7710) makes the LASAR 3-D camera, which can determine the distance to an object in the field of view. This camera generates both a conventional, intensity image and a corresponding range image. The image acquisition time for a 1024 × 1024 image is 7 s. Perceptron also supplies a software package with this system for bin picking—selecting randomly oriented parts from a bin.

3.3.2 Guidance Components

Many products were identified which could be useful in the development of a custom autonomous docking system. Several companies are listed to represent this category.

Telepresence, Inc. (604-873-3300), has a stereo viewing system intended to increase the operator's depth perception in teleoperated robotic applications such as hazardous materials handling, deep sea research, and medical surgical instruments. Their product uses a single lens and special viewing screen to display a stereo image. The operator must wear special spectacles with liquid crystal shutters to alternately present the left and right images to each eye 120 times a second.

Companies such as 3-D TV (415-479-3516) and StereoGraphics (800-783-2660) also produce special goggles and monitors to reproduce a stereo-like image. Stereo viewing could be used as an aid in manual docking operations by improving the depth perception. The degree to which stereo viewing would improve manual docking is uncertain.

Datacube (508-777-4200) builds high-speed image processing boards intended for integration in custom applications. The MaxVideo line can operate at up to 40-MHz clock speed. The boards provide a range of imaging functions that can be combined by the developer to meet the specific needs of the application. They also supply a suite of C language software development tools for rapid prototypes and testing.

Cognex (617-449-6030) markets a line of boards and systems for the VME and IBM PC buses. The boards are intended for image acquisition and processing. Cognex also has a C language library of vision and image processing software as well as application tools for tasks such as alignment marker location and print text quality inspection.

Automatix (508-667-7900) provides systems, frame grabbers, vision processors, and their C language image processing software environment for MacIntosh and VME platforms. The MacIntosh system has software modules that provide basic functionality in 3-D camera calibration, stereo cameras, or a single camera and structured light.

Southern Research Technologies (205-581-2900) offers the SRT-5000 video tracking board. This board has centroid, correlation, or coast modes for visible and ir target tracking and is available in a Mil-Spec version. It could be used by a systems integrator as part of an autodocking system but would similarly require that the operator initially identify the target.

3.3.3 Sensors

Polaroid Co. (800-225-1618) supplies an ultrasonic ranging system that can detect objects from 10.8 in. to 35 ft away. The system has a resolution of 1/8 in. for distances up to 10 ft and 1% of the reading for distances up to 35 ft. The ultrasonic sensors are point devices and do not scan an area. The ultrasonic output is 1-D, providing a range measurement to a single point in the scene. This is unlike that of a range camera, which has a 2-D field of view.

Logitech (510-795-8500) recently announced a 3-D computer mouse. The 3-D Mouse uses a configuration of ultrasonic transmitters and receivers to determine the position and orientation of an object in 3-D space.

Several companies produce 3-D range cameras—Odetics (714-758-0100), Servo Robot (514-655-4223), and Perceptron (313-478-7710). The camera scans the scene with an amplitude-modulated ir laser and calculates the range from the phase shift of the returned signal.

Teleos Research (415-328-8800) has the PRISM 3 system that computes target range using stereo images from a pair of video cameras. After an operator has selected a point in one image, the system locates that point in the other image with a correlation operator and estimates the range. The system does not provide the complete set of position and orientation parameters.

Many companies offer video cameras for machine vision applications. One product, the MC4013 from EG&G Reticon (408-738-1009), is representative of the market. The MC4013 is a high-resolution progressive scan charge-coupled device (CCD) camera. The output image is 1024 × 1024 pixels with a 30-Hz frame rate. Comparable video cameras are available from other companies, including Dalsa (519-886-6000), PULNiX (408-733-1560), Texas Instruments (214-917-1700), and Cohu (619-2776700).

3.4 INDUSTRIAL APPLICATIONS

The study looked for applications where autonomous docking with a robotic boom had been implemented and was technically mature. Of particular interest were industrial applications where autonomous guidance is considered routine. The study failed to locate any examples of true autodocking in practice, either in publications or through direct contact with vendors. The closest example of an industrial use for autonomous guidance is spacecraft docking.

3.4.1 Spacecraft Rendezvous and Docking

For over two decades, rendezvous and docking techniques have been studied and demonstrated by orbiting spacecraft. Rendezvous is the term used to describe bringing the two vehicles into near proximity to each other, typically within 1000 ft. Docking refers to the connection made between the two vehicles when the chase vehicle makes direct contact with the target vehicle and attaches to it.

The first automatic rendezvous and docking took place in 1967 by the Cosmos-188 mission of the Soviet Union. The Soviets used a radar transponder on the target satellite. The target satellite maintained a stationary attitude during the approach by the chase satellite. A probe and cone docking mechanism allowed the two vehicles to correct for a wide range of axial misalignment. The Soviet resupply satellite Progress has made 40 successful automatic docking missions without failure.[2]

In the United States, NASA has sponsored several studies with the goal of demonstrating autonomous docking by 1995.[2] Presently, satellite docking is pilot controlled at NASA. Much of the research at NASA appears directed toward unmanned, deep-space missions, where docking will be performed by a ground-based pilot. The desire to retain humans in the docking operation is probably due to their unequalled versatility and problem-solving skills. This capability is particularly advantageous during the early phases of development for a complex mission.

4. OPERATIONAL ISSUES AND CONCERNS

4.1 POTENTIAL VULNERABILITY RISK

A natural consequence of any electrical equipment is radiation of electromagnetic energy. Television monitors, radar, lasers, and video cameras all radiate energy. The same is true for some methods of target identification, most notably the special identifying labels and markers that were described earlier. For most electronic devices, the radiation level is so small that it is inconsequential in civilian use. Under certain circumstances, however, these emanations of energy could be detected by the enemy, making the emitter a potential military target. Although in most cases the radiation can be mitigated, the safety of the crew must be considered when selecting any electronic devices.

Because the minimum tolerable radiation level was not specified, this study investigated the techniques for autodocking regardless of the potential vulnerability of each method. The various methods for implementing the autodocking functions are described elsewhere in this report. To evaluate the competing methods, a higher priority is given to sensors that can be designed to minimize stray radiant energy. In other words, all other factors being equal, passive methods and sensors are chosen over active ones.

4.2 MECHANICAL CONCERNS

Mechanical concerns during operation include the mounting of the autodocking sensors, latching of the end effector to the AFAS port after docking, storage of these components during transport, and ability to withstand severe shocks and vibration both in storage and while docking. These concerns highlight critical operational design considerations that need to be addressed.

4.2.1 Mounting Configuration

Ideally, the autodocking sensor or sensors would be located at the end of the boom arm. In the case of a video camera, the optimum location would be at the end in the center. With this location the relative position between the sensor and the end of the supply arm is both fixed and minimized. As the arm moves closer to the port, the sensor also moves closer, enabling more accurate position determinations. If the sensor location was fixed with respect to the FARV body, then two pose determinations, one of the arm and one of the port, would be required, with a subsequent increase in errors. The distance of the sensor from the arm also affects errors because of the greater calibration error as the distance increases.

Placement of the sensor in the center of the arm, however, necessitates that it be moved from the projectile path once docking is completed. Design issues here include additional mechanical design to mount the sensor, facilitate its movement remotely, and ensure that the sensor position during the docking is highly repeatable and remains so for a large number of cycles of use. Mounting the sensor on the outside of the arm end is an alternative. This configuration would be an advantage only with a fixed mount. However, the sensor and mount could cause interference with the AFAS docking port and with the storage location.

4.2.2 Port Latching Mechanism

The autonomous docking subsystem and arm control subsystem will move the supply arm to the docking port on the FARV. At this point a mechanical latch on the port will mechanically complete the docking and seal the connecting parts. This latch will hold the arm in place at the correct position and orientation. The docking port mechanism will be able to latch the arm in place as long as the arm is within some tolerance of the nominal position. Accuracy and repeatability of the autonomous docking design are required to be less than this mechanical tolerance. Trade-offs are present in the mechanical complexity in the docking port and latch to achieve wider capture ranges vs the accuracy of the chosen autonomous docking pose determination method. Providing higher accuracy generally requires increased complexity and computational load. A practical limit, however, will be realized because of the required robustness and operation under severe environmental conditions.

4.2.3 Storage During Transport

During transport the autodocking sensors must be protected from dust and debris as well as being able to withstand temperature extremes, shocks, and vibrations. These factors must be considered both in sensor packaging as well as the mount design.

4.2.4 Shock and Vibration

The sensor mount and packaging must withstand levels of shock and vibration expected under battlefield conditions. In addition, mechanical motion must not alter the calibrated position of the sensor relative to the arm. Vibration during docking is also a concern because the accuracy of subsequent measurements may be reduced.

4.3 ELECTRICAL CONCERNS

Issues that affect the electrical operation of the autodocking sensors include the operating and storage temperature range, integration with the arm guidance control system, power requirements, and communications with operations personnel and other equipment such as diagnostics.

4.3.1 Temperature Range

When deployed, the autodocking equipment must operate in both cold, basic, and hot environments as defined by the Army.[37] The system is expected to function normally over an ambient temperature range of −46 to 49°C. During storage, the sensors and related equipment may be exposed to an ambient temperature range of −46 to 71°C. The actual operating environment for the autodocking system has not been determined.

4.3.2 Integration with Arm Guidance Control System

While the position determination portion of autodocking can be discussed separately from the arm guidance control system, in practice, this portion must be integrated with the arm guidance controls in order to physically accomplish the docking. The position determination provides feedback so that the arm control knows the relative port location and can compute the path necessary to move the arm to the correct position and orientation for docking.

Two visual feedback control approaches have been used in robot vision systems-absolute and differential.[38] Absolute vision feedback refers to the calculation of an absolute position measurement relative to the object of interest in an outer control loop, which is then used as the setpoint to an inner control loop to actually move the robot arm to that position. The goal is to reach a final position while keeping the object within view during motion of the object or the arm. Differential feedback is a closer coupling in which the difference between a measured feature and a setpoint is used to calculate a differential pose. Deviation of the object from the desired setpoint is used to command changes in the angles of the robot joints through inverse kinematics. The goal in this case is to maintain a position and orientation setpoint during relative motion of the arm and object. One advantage of the differential method is its greater tolerance of modelling errors. Either approach is a candidate for the FARV implementation.

4.3.3 Power

No special power requirements should be needed by the autodocking sensor other than the standard power available on the FARV. Reliability issues include determining whether redundant power buses are required.

4.3.4 Communications

Communications are required between autodocking and the various subsystems on the FARV. Control and status are required so that the operator is kept informed of the autodocking progress and so that the appropriate degree of manual control can be exercised. Position data and requests are transferred between the arm guidance control and autodocking. Status and testing requests are required by the diagnostics to ensure that all equipment is functioning properly.

4.4 ENVIRONMENTAL CONDITIONS

Environmental conditions pose a potential problem for the autodocking system. The outdoor environment includes rain and fog as well as extremes in temperature and illumination levels. Some environmental conditions can be compensated for through protective packaging and careful design. Poor weather conditions, when visibility is limited, are important to both automatic and manual docking. It is unclear at this point, which method is most appropriate to compensate for the lack of visibility in a heavy rainstorm. If docking during adverse weather conditions is required, it may be necessary to resort to an alternative sensor system that is immune to visibility limitations. A radar or possibly ultrasonic system may be a useful secondary method for increased reliability in all weather conditions. An infrared camera system may be the best compromise for the primary sensor.

The area surrounding the docking port on the AFAS will likely have special markers for identification and mechanical components for docking that could easily be damaged during transit. It is advisable to protect this important area with a tight-fitting enclosure to shield against the common roadway hazards. The docking mechanisms, such as the port alignment guides, interconnecting fittings, and the autodocking apparatus, could be inoperative if subjected to severe impacts from collisions. Similar problems could result from an accumulation of mud or road grime on crucial components.

If a video camera is used as a passive sensor, using natural illumination, the brightness extremes are a concern. Outdoor illumination levels can vary over an extremely wide range between midday sun to moonless night. The dynamic range of an electronic camera is insufficient to form an acceptable image under all conditions. The normal limitations of the camera can be compensated with special adapters that shift the camera's normal operating range. By incorporating several adapters, each designed to operate over a different part of the brightness range, the camera's operating range can be extended. An image intensifier can be used to form an acceptable image in low-light conditions, while neutral density filters can be used during daylight.

Another concern for a video camera is the minimum object distance parameter of the lens. Lens are designed to focus within a given range, typically from infinity down to the minimum object distance, and this range is determined by the lens design. If it is necessary to focus the lens on an object closer than the minimum distance, a compensation element must be introduced in the optical path. The lens can be compensated either with a close-up adapter or with an extension tube. Careful consideration should be given to the design of the optical components to ensure that the operational envelope of the autodocking system is within the lens focal range.

4.5 COMPUTATIONAL CONCERNS

Computational issues include speed, accuracy, and robustness. All are interrelated and depend both on the method chosen for pose determination and the implementation.

Computational speed as defined here is the time required to sense and calculate the pose. This time is a portion of the time required to perform autodocking and thus should be as short as practical. Algorithm complexity and hardware/software implementation as well as number of updates of the pose before docking determine the time interval. The implementation cost should be weighed against the method of pose determination.

Accuracy of the pose measurement also depends on the sensor, the chosen algorithm, and the number of times the pose is updated as the arm approaches the docking port. Sensor issues include image resolution, image and electronic noise, and mechanical stability during the measurement. Accuracy of calibration also must be maintained. Achieved accuracy is proportional to algorithm complexity and the number and level of scene features needed for processing. The actual required accuracy for docking is determined by the docking port mechanical design and the supply arm end mechanism.

Robustness refers to the ability of the position calculation method to maintain performance under adverse conditions such as poor visibility, dust, vibration, temperature extremes, etc. As previously discussed, a large number of methods have been developed which perform well under laboratory conditions. However, little is known in most cases about the effect of these environmental conditions. Consideration of these factors must be of prime importance when developing and evaluating the pose determination method.

4.6 OPERATOR CONCERNS

The autonomous system is by definition capable of operation without interaction with the operator. However, until further experience has been gained in autodocking in this application, some interaction with the operator may be necessary or even desired.

4.6.1 Degree of Autonomy

The ADS could be designed to have several levels of autonomy from the highest level of controlling the docking maneuver without operator involvement to the lowest level of serving as a simple video monitor.

The highest level of the hierarchy is complete autonomy intended for unsupervised operation. At this level, the operator has no direct involvement in docking after the autodocking sequence has been initiated. The autodocking system is responsible for identifying the docking port, determining the distance to the port and the angular orientation of the port, and supplying the six pose parameters (x, y, and z coordinates and roll, pitch, and yaw angles) to the control system. The control system then calculates the path to the port and moves the boom along that path. Optionally, the boom may stop at intermediate points along the path to allow the autodocking system to recompute the pose. As the boom approaches the port, the port grows larger in the field of view and increases the resolution of the pose measurement. Thus the accuracy of the pose calculation improves as the boom get closer to the contact point.

The next level is a semiautonomous mode where the operator is in the loop. Several options are available for semiautonomous operation. In one option, the autodocking system is nearly autonomous but requires operator initialization. In this method, the operator rather than the system must find the docking port in the 3-D image. The operator would identify the docking port by "pointing" to it using a touch screen CRT or other similar device. After the port has been identified by the operator, the autodocking system would resume fully autonomous operation and would track the location of the port as the boom advances.

Another possibility is a shared mode where control is shared between the autodocking system and the operator. In this mode, the x-y position is maintained under manual control by the operator, and the distance to the contact point is maintained automatically. This mode combines the better depth perception of the autodocking system with the strong relative position judgment of the human.

Another alternative semiautonomous mode would be to let the operator be in full control of the boom and use the autodocking system to provide direction cues. This could take the form of direction arrows on a CRT screen advising the operator to move in a particular direction in order to align the boom with the docking port. Additionally, the responses of the autodocking system could be recorded for later analysis. This would be useful, especially in the early phases of development when it is beneficial to compare the autonomous and manual modes to gain confidence in the system.

The lowest level of the hierarchy is manual operation with vision assist. In this mode, the operator would be responsible for all aspects of boom control. The autodocking system would be inactive except for the image acquisition sensor, which would provide a booms-eye view of the docking approach. This mode is only suitable for video camera sensors because the output of other types of sensors, notably the radar and ultrasonic, is not easily interpreted by humans.

Because a single camera image lacks full depth information, some techniques require multiple cameras to reconstruct a 3-D representation of the environment. If the operator views each camera through a conventional CRT monitor at normal viewing distance, he loses the depth cues from binocular vision. Products are available which simulate binocular vision with stereo cameras. One method uses two miniature television screens that each display an image from one camera. The television screens are mounted on special goggles worn by the operator. The goggles are designed to isolate the left and right image to each eye, replicating natural binocular vision. Another method is to combine two images onto a single CRT screen to recreate depth. Both of these methods have demonstrated some success in practice by improving the operator's depth perception. As yet, these systems do not enjoy wide acceptance by users because they do not exactly replicate normal binocular vision and consequently require a period of adjustment before the operator feels comfortable using them.

4.7 FAILURE MODES

Reliability of the docking process and associated equipment is of prime importance. While a reliability analysis of autodocking is beyond the scope of this report, issues that affect reliability and possible failure modes are given here. This subsystem is assumed to consist of a sensor located on the arm, a target located near the docking port, and a computer system to calculate the pose from the sensor information. Failure of any one of these pieces could render autodocking inoperative. Diagnostics should be provided to test each component and to inform the operator of any failures.

Redundant systems, when properly designed, increase reliability and enable continued operation with full capabilities or with reduced functionality in the event of single or multiple failures. Failure modes need to be analyzed and trade-offs made based on cost and complexity to determine the required functionality for each level of failure. In general, two types of redundancy can be provided: (1) multiple systems using similar design and (2) functional redundancy with multiple systems of different design. Each type has advantages and disadvantages that are discussed below.

Redundancy using similar design increases reliability by replicating subsystems that are identical or similar in design. Failures in a subsystem can be directly detected by comparison with the redundant component. Reliability analysis is easier with this method. However, operating limits using this approach are not changed and performance is not improved.

Improving reliability through multiple systems of different designs is an alternate approach. An example might be the use of a single-vision camera for pose determination along with a redundant system using ultrasonic sensors. The same measurement is made through different means. The advantage is that higher reliability may be achieved under severe environmental conditions. Cameras may produce poor to nonexistent images under foggy conditions, for instance; but ultrasonic sensors could continue to operate without problem. The result is an improvement in reliability due to component failures as well as an expansion of operating conditions.

At some point, whether with single or multiple failures as determined by the design trade-off analysis, the totally autonomous docking function may become inoperative. The design should then provide degrees of reduced capability and increasing manual control. These capabilities could be the modes of operation discussed previously from fully autonomous to fully manual where the operator moves the supply arm through teleoperated controls. Diagnostics provided to the operator should indicate the state of the system, including failures.

5. CONCLUSIONS

5.1 SUMMARY

It was shown that a generic autonomous docking system must be capable of performing the following major functions: (1) acquiring a 3-D image, (2) identifying the target in that image, and (3) determining the position and orientation of the target. The term "image" is used here as a representation of the distance to an arbitrary region in the field of view, independent of the implementation method. For example, an ultrasonic image may consist of a single element, while other methods such as the video camera may have millions of elements. The choice of image sensor must be considered carefully because the characteristics of the sensor will also influence the design of the target identification and pose determination functions.

5.1.1 Active Devices vs Passive

A key factor in the sensor selection is the operating mode for the image acquisition subsystem. The image acquisition subsystem can be designed to operate in an active mode or in a passive mode. An active sensor uses a transmitter to emit energy from the sensor toward the target. The emitted energy may be the directed beam of light used in laser cameras or a widely dispersed rf pulse of a radar camera. A receiver located near the transmitter measures the energy reflected from various objects in the field of view. In an alternate active configuration the transmitter is attached to the target. The receiver measures the energy directly emitted by the target in order to identify and locate it. A communication link between the receiver and transmitter is needed if the emissions must be synchronized to the receiver. This technique has been implemented with video cameras using illuminated targets, ultrasonics, or radar techniques. Examples of active mode configurations are radar, laser, and video camera when used with contrived illumination and ultrasonics. In the passive mode, direct emission is unnecessary because the sensor measures the naturally occurring energy radiated from the target. An example of passive mode is a video camera, which uses ambient light as the transmitter and measures the light reflected by the target.

The potential techniques considered for the image acquisition sensor include video cameras, laser range cameras, ultrasonics, and radar. All can be used for active mode configurations. The video camera technique was the only sensing method reported that is capable of passive operation. The overwhelming majority of cases reported in the literature used one or more video cameras for the image acquisition sensor. In most cases, the video camera was chosen because of its inherent simplicity, low cost, and widespread availability. In addition, the video display is familiar and easily interpreted by humans. This natural correspondence to biological vision is convenient when the system must also support manual operation. In the FARV application, a single video camera could be used for both autonomous docking and for manual operation. It is not clear how beneficial another method such as an ultrasonic system would be during manual docking.

NASA and the Canadian Space Agency have sponsored most of the research and development on autonomous docking to date. These agencies were the groups found to be pursuing autonomous docking. Commercial products were found that could have applications for bin-picking or robotic guidance, but these products were often originally intended for space docking. It should be noted that NASA, which has been studying autonomous docking for over two decades, is planning to use vision-based methods for unmanned exploration of deep space.

Several methods of target identification have been described. The target identification technique is influenced by the type of imaging sensor. For example, if radar imaging is preferred, then shape analysis is not meaningful for target identification. Some target identification methods, such as those requiring flashing lamps, are incompatible with the definition of passive operation. It should be stated that configurations can be designed that limit the coverage range of active devices, thereby minimizing their detectability by external observers.

Before the final implementation, a key technical challenge must be overcome. The environmental conditions that characterize field use will pose a challenge that is common to all the techniques discussed in this section. The external sensors will be exposed to shock, temperature extremes, dust, mud, and other environmental hazards. While each type of sensor has a vulnerability to one or more of these hazards, the risk can be managed. The more fragile components may need special environmental enclosures for protection. The environmental hazards are daunting but have been mitigated before and should not prevent field implementation.

5.1.2 Recommendations

The different techniques of image sensing can be evaluated by comparing each according to the following desirable features:

1. Passive sensing, the ability to operate without emanating energy.
2. Passive target, the ability to operate without a communication link to activate a signaling device on the target.
3. Compatibility with manual operation; the output is understandable to a human and could be used for teleoperation.
4. Autodocking history; the method has been demonstrated for autodocking applications in the laboratory.
5. Range; the sensor can be made to operate at the expected operating distances.
6. Accuracy; the certainty or confidence that a given range measurement is correct.
7. Reliability; the method can be made rugged for field operations.

Each method is rated high, medium, or low in each category in Table 1. The ratings are assigned on the basis of data obtained from the publications in the references and the experience of the authors.

Based on these criteria, it is clear from the table that the video camera is the preferred image acquisition sensor. The laser camera and ultrasonic sensors are identical in their ranking. The laser range camera is very similar to the video camera except for the manner of 3-D calculation. The difference between the video and ultrasonic method makes it a reasonable alternative approach to the video method. An ultrasonic sensor would be a useful secondary sensor, taking over if the camera is inoperable. A hybrid system combining video and ultrasonics is promising. A hybrid system was not identified in the commercial survey, but could be developed if necessary. Radar is the least preferred method because it is more suited for long distance use and is not considered appropriate for close-range docking. Given the desire for passive operation, the preferred method of target identification is either shape analysis or a passive target label. Both of these target identification techniques are typically used in conjunction with model-based pose determination.

Table 1. **Comparison of autodocking sensors**

	Video	Laser	Ultrasonic	Radar
Passive sensing	H	L	L	L
Passive target	H	H	M	M
Manual compatibility	H	M	L	L
Autodocking history	H	L	M	L
Range	H	H	M	L
Accuracy	H	M	M	L
Reliability	M	L	H	H

Because the technology is evolving at such a rapid pace, any equipment used initially will likely be rendered outmoded. For this reason, it is recommended that the autodocking system be designed to maximize the modularity of its functions. This will increase the chances of updating the hardware as newer and better equipment becomes available.

5.1.3 Forecast

Autonomous docking was first demonstrated in 1967. Originally limited to space applications, more recent developments in robotics have created an increased demand for advanced vision capabilities in other areas, such as industry and manufacturing.[39] Even though it is over 25 years old, autonomous docking is still in the embryonic stage. A major impediment thus far has been the lack of a real demand for autonomous guidance outside of NASA. The increasing use of robots for industrial applications will spur development of a more "human-like" vision system. Research tends to lead commercialization by several years. The technology being discovered today could be seen in everyday life tomorrow. There is a significant research effort in the universities to develop autonomous visual capabilities. We can thus expect major advances in both the theory and implementation of autonomous vision over the next 5 years. The results of recent research are now appearing in commercial products with performance that was unthinkable 10 years ago. Even though autonomous vision is a leading edge technology today, many experts believe it will be commonplace in the future, as the technology continues to mature.

The forecast for autonomous docking of the FARV is favorable. Several techniques for autonomous robotic guidance have been successfully demonstrated under controlled conditions. The hardware needed to implement an autodocking system on the FARV is available but largely unproven outside the laboratory. Any unresolved performance issues should be answered through field tests with an operational prototype. The greatest technical challenge to overcome seems to be accommodating the environmental extremes that are expected in FARV field operations. Autonomous docking is a leading edge technology but is sufficiently mature that it should be considered feasible.

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Appendix A

VENDOR CONTACT LIST

The following companies participated in the survey of commercial systems:

3D TV Corp
ABB Robotic
Adept Technology, Inc.
Advanced Visual Systems
Air Gage
Applied Scanning Technology
Applied Technologies
ASI Robotics
Automatix
Azimuth
Cognex Corporation
Conrac Display Products
Cooke Corp
Cybernetic Systems and Automation
Datacube, Inc.
Delta Tau
Dynatech Lab & Imaging
Eshed Robotec
Hadland Photonics
Imaging Automation
Imago Machine Vision, Inc.
Industrial Perception Systems, Inc.
Innovision
Intelledex Vision Products
Keyence
Kinetic Sciences, Inc.
Kohol Systems
Laser Design, Inc.
Matrox
Medar, Inc.
Nomadic Technologies
Odetics
Omnicomp Graphics Corp.
Perceptron, Inc.
Phoenix Imaging
Polaroid Corp Ultrasonics Components Group
Precision Robots, Inc.
PsiTech
Robosys
Robotics and Automation Controls
Servo Robot, Inc.
Sharp Digital Information Products
Sonatech
Southern Research Technologies
Spectronics, Inc.
StereoGraphics Corp
StereoScope International
Synthetic Vision Systems
Tau Corporation
Technical Arts
Tecnomatix Technologies/Robcad
Teleos Research
Telepresence, Inc.
TeleRobotics Int (TRI)
Universal Technology, Inc.
Universal Imaging
Visual Numerics
Visual Sense Systems

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