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VISUAL SERVOING : A TECHNOLOGY IN SEARCH OF AN APPLICATION

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Abstract

Considerable research has been performed on Robotic Visual Servoing (RVS) over the past decade. Using real-time visual feedback, researchers have demonstrated that robotic systems can pick up moving parts, insert bolts, apply sealant, and guide vehicles. With the rapid improvements being made in computing and image processing hardware, one would expect that every robot manufacturer would have a RVS option by the end of the 1990s.

So why aren't the Fanucs, ABBs, Adepts, and Motomans of the world investing heavily in RVS? I would suggest four reasons: cost, complexity, reliability, and lack of demand. Solutions to the first three are approaching the point where RVS could be commercially available; however, the lack of demand is keeping RVS from becoming a reality in the near future.

A new set of applications is needed to focus near term RVS development. These must be applications which currently do not have solutions. Once developed and working in one application area, the technology is more likely to quickly spread to other areas. DOE has several applications that are looking for technological solutions, such as agile weapons production, weapons disassembly, decontamination and dismantlement of nuclear facilities, and hazardous waste remediation. This paper will examine a few of these areas and suggest directions for application-driven visual servoing research.

1 Introduction

Vision has been used with robots as far back as 1967, just 6 years after Unimation, the first U.S. robot manufacturer, delivered its first robot arm. At that time, Wichman [1] used a vidicon camera and a robot arm to locate, stack, and align two white blocks on a black background. Even then, researchers realized that vision could improve robot performance. Wichman states that his original intent was

> "to redeem the flaws of a basically untrustworthy arm by substituting a visual feedback system for the final stages of the stack servoing."

While successful at stacking blocks, Wichman's final system fulfilled only part of its original intent. Due to the low resolution of the camera system, Wichman concludes:

> "it uses visual feedback only to command new arm positions, which will be achieved by kinesthesis, rather than establishing a closed loop abandoning precise kinesthesis in favor of strictly visual measurements."

Using visual feedback to command open loop robot positions became the industrial standard for the next 26 years. However, Wichman's original intent of closing the loop around the visual information – now referred to as "visual servoing" – is realizable today.

For the purpose of this paper, I will define Robotic Visual Servoing (RVS) as the use of real-time visual information to control a robot end-effector's position either relative to a world coordinate frame or relative to the object being manipulated. RVS comes in many different flavors from fixed or end-effector-mounted cameras, to monocular or binocular vision, to planar or complete 3D motion control. An excellent overview and history of RVS can be found in [2].

Over the past decade, visual servoing research has flourished because of recent advances in personal computing, CCD cameras, and image processing hardware. These advances have made it possible to process images at frame rate (60Hz) and extract the appropriate image features for robotic control. Researchers have demonstrated that vision guided robots can track and pick up objects moving at 300mm/s [3], track weld seams [4], apply sealant at 400mm/s [5], perform part mating operations [6], and guide vehicles moving at 96km/h [7]. Table 1 shows a list of tasks that have been demonstrated. Detailed references can be found in [2].

Given that there are successfully demonstrated RVS systems, why aren't the robot manufacturers in-

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Table 1: Demonstrated Visual Servoing Tasks.

Bolt Insertion
Conveyor Belt Picking
Connector Acquisition
Weld Seal Tracking
Sealant Application
High-Bandwidth Planar Positioner
Part Mating
Road Vehicle Guidance
Telerobotics
Fruit Picking
Ping-Pong
Juggling
Inverted Pendulum Balancing
Labyrinth Game

corporating RVS into their systems? I would suggest four reasons:

1. cost,
2. complexity,
3. reliability, and
4. lack of demand.

Let's look at each of these individually.

Cost is probably the weakest obstacle and the one which is diminishing the fastest. Most commercial robot manufacturers already provide vision packages as optional equipment. These packages are typically used to recognize an object and determine its x,y position and planar orientation. Some even provide grey level image processing and can recognize overlapping objects. In many cases, the cost of higher speed image processing boards has already dropped from the $20,000 range to the $5,000 range. This drop in cost should be accelerated by the recent explosion of home computer multimedia hardware and software.

By complexity, I am referring to the user unfriendliness of most high-speed image processing systems. Many require that the operator understand algorithms for image convolution, edge detection, feature extraction, synchronization, DOS/UNIX, programming languages, etc.. The operator on the factory floor does not have this knowledge. The vision systems provided by the robot manufacturers are typically very high level, often automatically learning the part by presenting the part to the camera in a number of orientations [8]. A high level MacIntosh-like interface will be required for commercial implementation of an RVS system. Complexity is another area that will greatly benefit from the explosion in home computer multimedia and, therefore, should be a diminishing obstacle for an RVS system.

By reliability, I am referring to the need for the vision system to adapt to environmental changes such as lighting variations and changes in part orientation. For example, the main obstacle at General Motors is the dirty industrial environment which cause the lenses and optical components become obsured. These are factors which often complicate the use of vision in the industrial environment. These are difficult problems which are slowly being resolved. Not withstanding, these constraints should not prevent the realization of an industrial RVS system. The fact that robot manufacturers offer vision systems with these constraints today makes me believe that an RVS system could also be implemented with the same constraints.

I believe that lack of demand is currently the main obstacle preventing robot manufacturers from actively pursuing an RVS system. Some of the tasks listed in Table 1 are true industrial problems. However, just because a task can be performed with RVS does not necessarily mean that RVS is required. For example, simply picking a part off a conveyor belt is a task that can be performed without visual servoing. This is accomplished in industry by using a projected light strip to determine the object pose and a tachometer on the conveyor belt to estimate its speed. Another example is part mating. RVS could be used to mate two parts regardless of part presentation, but it is simpler and more cost effective to build a fixture to hold the parts in the proper orientation.

The key to near term commercialization of RVS will be to find those applications for which there are no other available technologies and RVS is required today. Typically, these will be applications where precise positioning is required in an uncertain and possibly dynamic environment. RVS benefits over static vision in that an RVS error-driven control law will improve the relative positioning accuracy even in the presence of modeling (robot, camera, or object) uncertainties. An example for which this is important is fixtureless assembly in a small lot manufacturing environment. For years, researchers have been suggesting that RVS will be a vital component in small lot manufacturing. Unfortunately, very few companies can afford to use robotics in a small lot manufacturing environment. Most robotic systems are being used for medium to large lot manufacturing where it is considerably less expensive to design the manufacturing process around hard fixturing. Without customers for RVS, the robot manufacturers will not pursue the technology.

To encourage the near term development of RVS systems, a new set of applications must be pursued. The following two sections will brainstorm on new applications for RVS in both structured and unstructured environments. A few applications, which Sandia National Laboratories and the U.S. Department of Energy are involved with, will be discussed in detail. Specifically, these include agile weapons production, weapons disassembly, decontamination and dismantlement of nuclear facilities, and hazardous waste remediation. The objective of these sections is to encourage a more application-driven approach to visual servoing research and development.

2 Structured Environment

I will start first with applications in structured environments since knowledge of the workpiece simplifies the visual servoing task considerably. By a structured environment, it is assumed that some information about the part to be manipulated is known. The types of information needed are the positions of visible and recognizable features on the part, feature tolerances, and possibly its coloring and surface texture. The position information is needed in order to control the position and orientation of the part. For example, Feddema [9] showed that it is possible to track both the object's 3D position and orientation (pose) with a single camera if the position of three or more visible features are known. The tolerance information would help select the features for control and determine the theoretical accuracy with which the part could be positioned. The coloring and surface data would be used off-line to determine and test the image processing routines needed to perform the visual servoing.

The position information would come from two sources. For new parts, the position information would most likely come from a solid or boundary representation model of the part as designed with a CAD package. While not currently commercially available, tolerance, color, and texture information could also be included in the CAD model. For existing parts, the surface data would be generated with a 3D laser scanner. Feature points could then be extracted manually or with some sort of automatic feature extraction routine. Tolerance, color, and texture information would be entered manually and/or determined from still images.

Just as a brainstorming exercise, I have listed several applications in structured environments which might require an RVS system. This is not an all-inclusive list, and I will only briefly discuss the first few while going into more detail about Sandia's applications. The first three are in the Microelectronics field. It is surprising how many people, mostly women with very steady hands, still assemble and test ICs and printed circuit boards today. These are very difficult jobs especially as IC features drop below micrometer sizes. A miniaturized planar robotic system with RVS would be a much more efficient and repeatable method [10]. For larger clean room applications, Adept's static vision package [8] has been used extensively for IC Insertion. Adding a closed loop RVS system should improve positioning performance and shorten cycle time.

Table 2: Visual Servoing Applications in Structured Environments.

PC Board Soldering and Testing
IC Insertion
Component Cleaning
Space Structure Assembly
Textile Manufacturing
Composite Layout
Small Lot Manufacturing
Agile Nuclear Weapons Production
Nuclear Weapons Disassembly

Onother possible RVS application is the assembly of space structures [11]. In 1991, I saw a demonstration at NASA-Langley where a domino pattern next to the truss socket was used to guide the robotic assembly of the structure. A "static look-and-move" approach, much like that performed by Wichman in 1967, was being used. Again, adding a closed loop RVS system should improve positioning performance and shorten cycle time.

As mentioned in the introduction, small lot manufacturing is one area that would benefit from RVS. Currently, one-of-a-kind fixturing is developed for each robotic assembly operation. In a small lot environment, the design and fabrication of fixturing can be a substantial portion of the manufacturing costs. In addition, the downtime of the robot for testing must also be included. The perceived cost of an RVS system would be reduced by amortizing over the life of several products. Fixturing and downtime would be reduced.

To take this one step further, Sandia National Laboratories is looking at the feasibility of agile nuclear weapons production. This is essentially the ability to cost effectively produce a lot size of one. Robotics is believed to play a vital role because it will reduce the exposure of humans to radioactive materials. The ultimate goal of this agile manufacturing system would be to enter the CAD design of the product into the computer and out would come the manufactured product with minimal human intervention.

As an illustration, consider manufacturing a custom gear box. The design of the gear box is entered into a CAD package. This design is sent to a Computer Numerically Controller (CNC) machine where the gears and the box are cut out of steel. A robotic arm loads the raw steel, unloads the finished gears and box, and assembles the components. When loading the steel, static vision as opposed to RVS is used to locate the raw stock in a bin. RVS is required unless precise placement of the end-effector is needed or the stock is moving on a conveyor belt at an unknown speed. After the parts are machined, the robot retrieves the part using static vision and places it on a table.

An automated assembly planner then generates an assembly sequence which is downloaded to the robot controller. Previous work [12] assumed that the mechanical fixturing would also be designed by the assembly planner. However, with RVS this would not be required. Instead, the assembly planner would simulate the visual environment and develop an assembly plan based on visual constraints [13]. The visual compliant motions along with suggested image processing routines would be downloaded to the robot controller. During the assembly, the suggested image features would be tracked during the placement of the gears.

Another application within the DOE which could require RVS is the automated disassembly of the nuclear warheads. This is a dangerous task that not only includes radiation exposure but also the possibility of detonation of non-nuclear explosive materials. To make matters more difficult, many of the components of these weapons are as-built and considerably different from their design drawings. This disassembly would include not only removing the weapon's nuclear component, but also the removal of gold, lead, and other non-EPA disposable materials. As in the previous example, a disassembly planner could be used to simulate the visual environment and develop a disassembly plan based on visual constraints. However, in actual execution of the task the RVS system would have to adapt its plan based on new visual information and human input. Figure 1 shows a block diagram of the required modules for agile manufacturing and weapons disassembly.

Based on the above scenarios, future RVS research and development is needed in the following areas.

1. Development of computer simulators which graphically display what a camera will see during a visual compliant motion. The simulator should include lighting and texture.

2. Development of robust image feature selection algorithms which take into account the task to be performed and variations in lighting and tolerances. These algorithms should be used in coordination with the graphically simulated images to select image features and image processing routines off-line.

3. Development of adaptive schemes for updating the world models in the computer simulation based on new visual information obtained while performing a motion.

3 Unstructured Environment

Visual servoing in an unstructured environment can be a much more difficult task. Without knowledge of the part, it is impossible to determine the depth of the object from a single image. Some recent RVS research has looked at discerning depth from a moving camera [14]. The key to this approach is keeping track of point correspondences between consecutive images. Two other possibilities are to use stereo cameras or a simplified structured lighting system which only keys on small regions of interest. The stereo cameras depend on determining point correspondences between the stereo views. The simplified structured lighting idea is to direct laser light at those locations where you need to determine depth and view them through the visual servoing camera.

Table 3: Visual Servoing Applications in Unstructured Environments.

Decontamination and Dismantlement
Hazardous Waste Remediation
Remote Surgery
Aligning Stereo Camera
Automated TV Camera Guidance

Again, I have listed a few RVS applications in Table 3 of which I will only discuss those which Sandia National Laboratories are involved in. Sandia National Laboratories is part of multi-lab effort to develop robotic technologies for the environmental remediation of DOE's facilities. The focus areas within this program include contaminant analysis automation, mixed waste operations, tank waste remediation, and decontamination and dismantlement (D&D). The last three applications involve unstructured environments where RVS could play an important role.

Many of DOE's weapons production facilities have been shut down because of end of the cold war and environmental safety concerns. Many of the buildings which were used to produce the U.S. weapons stockpile have been left vacant. New regulatory requirements are driving the decontamination and dismantlement of these buildings. Some information regarding site maps is known, but in many cases the facilities have been modified and the drawings have not been updated. The scenario would be for a team of robotic vehicles to enter these facilities and survey and characterize the area. Afterwards, the vehicles would enter with pipe cutters, sledge hammers, and power saws to remove asbestos and radioactively contaminated materials. This type of project would take many man-years of effort with a strictly teleoperated system. To reduce operator fatigue and shorten the remediation time, telerobotic systems with some forms of autonomy are being suggested.

Robotic visual servoing could be used to guide pipe cutters, sledge hammers, and power saws, in addition to picking up debris. Considerably more human interaction will be required than for structured environments. A control scheme which allows the operator to quickly and easily modify the visual servoing task is needed. The interaction could be a combination of computer graphics and live video monitors. For example, Sandia currently uses a visual targeting system to estimate the position of an object. The operator points to the same object in two different screens and triangulation is used to estimate its 3D position. The visual targeting is not always accurate enough to manipulate the object; therefore, it would be helpful if an RVS system could be switched on during the approach to the object.

The estimated positions would be used to start the servoing process. The operator would then manipulate a set of cursors on a live video image to drag the gripper to the appropriate grasping position. Image features would be used to automatically guide the robot motion.

Sandia is also involved in the remediation of DOE's underground storage tanks and buried waste sites. The underground storage tanks can be as large as 75 ft. in diameter and 35 ft. deep and hold up to 1 million gallons of radioactive waste. Entry to these tanks is through 12 to 42 inch risers in the top of the tank. Westinghouse Hanford Company has contracted with SPAR, Inc., to develop a robotic arm to be used for characterization of the inside of these tanks. This arm will be equipped with cameras and chemical, radiological, and physical characterization instrumentation. Data extracted with this arm will be used to plan remediation of the tanks. A much larger arm will possibly be used to remove loose items, cut out thermocouple trees, and carry waste removal end-effectors. A graphical user interface which contains computer models of the environment will be used to plan tasks and telerobotically control the arms [15]. Unfortunately, the models will not always be accurate and human intervention will be needed in many cases to manipulate the environment. Again, visual servoing could be used to help guide characterization sensors, pipe cutters, and waste removal tools. Figure 2 shows a block diagram of the required modules for D&D and hazardous waste remediation.

In addition to the research and development areas suggested in the structured environments, future R&D for unstructured environments should include:

1. Determining depth from motion while performing RVS.
2. Development of visual servoing end-effector hardware. Must be small, adjustable, and not interfere with robot grasping.
3. Development of an interactive video screen for directing RVS.
4. Combining visual targeting with RVS.

4 Conclusion

Visual servoing opens the doors for robotics to a whole new realm of human-like capabilities including fixtureless assembly/disassembly, composite layout, textile manufacturing, and vehicle guidance. Unfortunately, its cost, complexity, reliability, and lack of demand are keeping it from being commercialized. In this age of less research and more applied development, it is important to find those applications for a technology which will quickly progress it to commercialization. In this paper, I suggest that many of DOE's robotic applications may be a driving force which will prompt the robot manufacturers to commercialize visual servoing. However, the usefulness of robotic visual servoing in these applications must be demonstrated first. To this end, several areas of applied research and development were listed which would promote such a demonstration.

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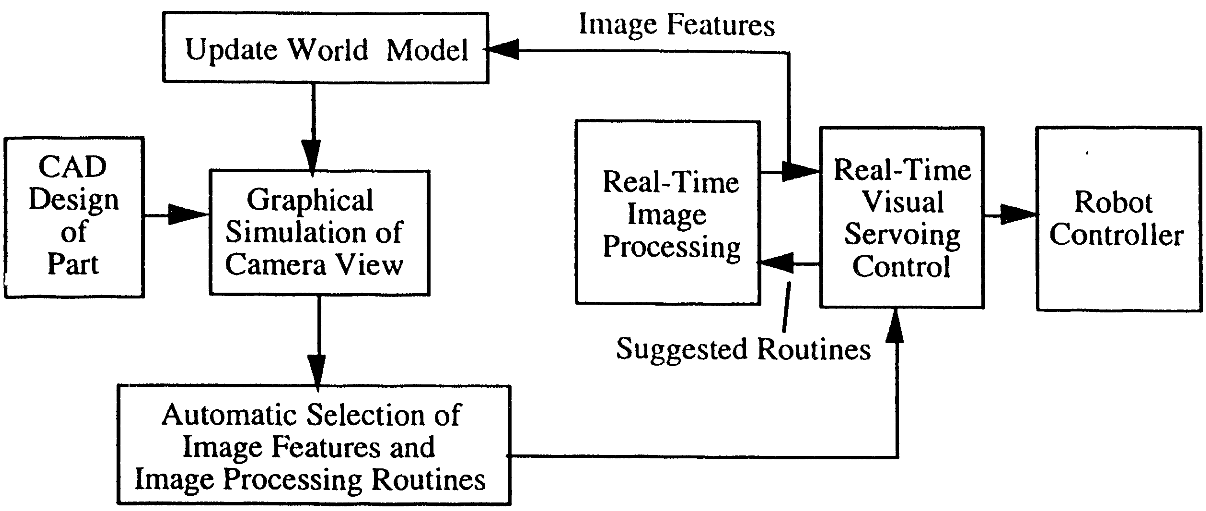

Figure 1. Modules of an RVS system for agile manufacturing and weapons disassembly.

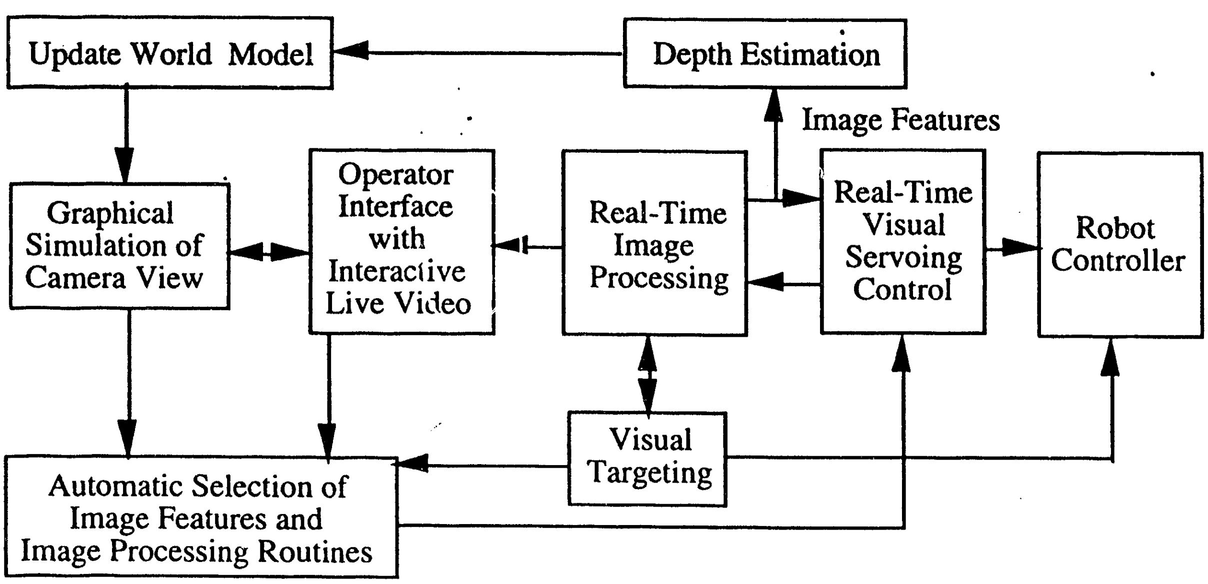

Figure 2. Components of an RVS system for decontamination and dismantlement of nuclear production facilities and for hazardous waste remediation.