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VISION ASSISTED DISASSEMBLY USING A DEXTEROUS HAND-ARM-SYSTEM: AN EXAMPLE AND EXPERIMENTAL RESULTS

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Abstract. Future applications in automation of non-destructive disassembly processes – necessary and important for re-use of components – require highly sensorized and dexterous robot systems. The main elements of the presented system are a disassembly sequence planner using special elementary disassembly operations, a redundant hand-arm-system with fifteen degrees of freedom supplied by a six-axes robot and a three-fingered gripper, and a vision system used for offline grasp and motion planning as well as for online supervision. Besides a description of the overall system structure and explanation of the underlying ideas for special disassembly operations, the presentation of first results and experiences from disassembling some parts of a video camera recorder will be one of the central points to be discussed.

Key Words. hand-arm-eye system; grasp planning; hand-arm-coordination; disassembly; vision.

1 Introduction

For environmental and economical reasons future applications in automation will focus on robot assisted disassembly of a large variety of electronic products with the general aim to re-use valuable modules and components recovered from old products. Making re-use possible will increase the added value of recycling factories and moreover, it will reduce the negative environmental impacts of end-of-life electronic products. Especially the non-destructive disassembly of highly developed electronic products is a difficult task requiring complex disassembly operations because up to now only little attention was paid to facilitate disassembly in the stage of product design. Due to the compressed structure of these products there is a lack of clearance, so that the respective parts to be disassembled are hardly accessible and graspable. Furthermore, fasteners and other connections (e.g. snaping, locking) have to be removed, which is not always possible without destruction.

Besides however, disassembly cannot be considered simply as the reversal of assembly because of a raised uncertainty. The condition of the product to be disassembled may change during its life-cycle and disassembly difficulties due to ageing, use or unprofessional product repair occur. Object models based on the product state of assembly cannot be used unrestrictedly or they are not completely available, and therefore rich sensor information is necessary for acquisition of adequate object information. Due to the uncertain object condition and difficult graspability and accessibility, it is reasonable to use vision for offline grasp and motion planning as well as for online supervision. In order to cope with another main difficulty, the jamming and wedging of the parts to be disassembled, strategies based on force/torque sensor information are necessary. Additionally, strategies have to be developed to handle the great number of cables within electronic products.

Since disassembly is a relatively new task in flexible robot manipulation processes only a few direct approaches can be found in literature, but in most cases the real conditions are disregarded and the topic is very restricted, as for example [Woo and Dutta 91] or [Hoffman 89] where only translational robot motions, rigid components and no fasteners are considered. A few general approaches for planning of local fine motions exist ([Wilson and Matsui 92], [Zussmann et. al. 92]), but they are based on geometric reasoning only. Motivations for long term research and a theoretical and applicative framework for approaching disassembly problems in robotics were given by [Dario and Rucci 93]. But the greatest lack of the presented approaches is the absence of experimental results with a robotic system under real conditions and exactly this is our first interest.

This paper presents a description of the overall system structure and the explanation of the underlying ideas for special disassembly operations. Moreover, first results and experiences from disassembling the top of a video camera recorder will be one of the central points to be discussed. Especially the connection and interaction of the complex robotic system, visual inspection and other sensor information will be described.

2 System Overview

A fundamental demand on flexible autonomous robot systems is the combination of flexible actuators, various sensors and adequate information processing: Intelligent robots interact with the real world by employing sensory information to perceive their environment as well as flexible, redundant actuators to change the state of their environment.

The system (fig. 1) presented in this paper comprises a six-axes *manutec r3* puma type robot arm, a three-fingered dexterous gripper with three joints per finger and a multi-camera imaging system for scene analysis. The experimental gripper (fig. 2) was developed and built at the Darmstadt University of Technology [Paetsch and Kaneko 90]. Employing a multi-fingered hand increases the number of degrees of freedom of a robot system and by that means the system flexibility is increased. But using the specific capabilities of the dexterous robot gripper within the complete system requires hand-arm-coordination, explained in section 4. This highly redundant coordinated hand-arm-system allows dexterous manipulations necessary for complex and skilful disassembly operations. In order to perceive

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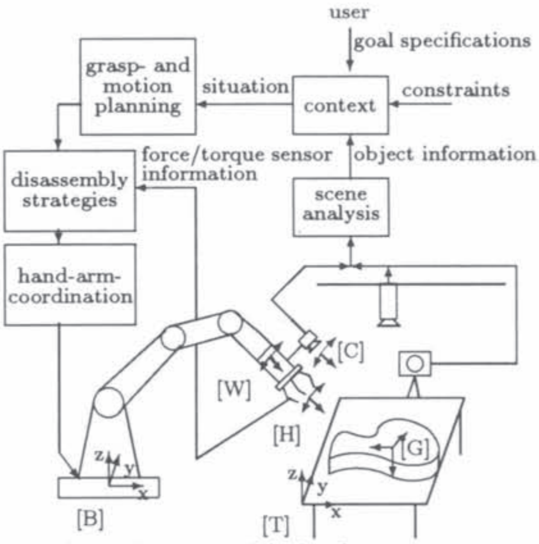


Fig. 1. Structure of the hand-arm-eye system.

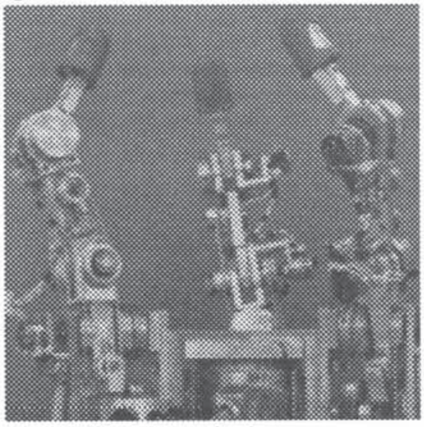


Fig. 2. Experimental gripper.

adequate object information the system provides task-oriented image processing in addition to force/torque sensor information. For this a mobile camera is mounted on the robot arm to achieve 3D-information about the robot work space in connection with two static scene cameras enabling the vision system to guide the robot. An essential task for such a robot vision system is planning stable grasps to be performed by the gripper.

3 Vision Assisted Grasp Planning

The planning of stable grasps for a multi-fingered gripper is a complex task, especially if the shape of the body to be grasped is unregular. In order to avoid analyses of the entire object a two stage visual inspection process is employed. At first the system determines the cartesian location and coarse size of each object in the scene by evaluation of object features in a binary image sequence. Guided by these features the system decides whether the gripper should approach the object perpendicular to its top face or to one of its side faces. Through this decision the grasp plane is determined in which the fingers of the gripper should contact the object for grasping.

In the second stage an extreme data reduction of images is performed by extraction of silhouettes and contours in order to obtain a contour of the grasp face at which the fingers should contact the object. From this contour features are extracted characterizing object areas favourable for grasping like concave contour parts. The combination of these features with goal specifications due to the given task and the gripper geometry specifies the given grasp context (cf. fig. 1). Context information allows a selection of the specific grasp situation characterized by the grasp mode to be employed as well as by favourable contour parts within the selected grasp plane. The employed system provides planning algorithms for several grasp situations described in detail in [Seitz et. al. 93].

This paper will focus on two grasp situations interesting for grasping the relatively flat but unregularly shaped top of a video camera recorder (camcorder with movable viewfinder, see fig. 8). Approaching the gripper perpendicular to the top face of the camcorder either a palmar fingertip grasp can be performed in presence of many long and plane contour parts (fig. 3a) or, for the sake of stability, a circular fingertip grasp can be applied to concave contour parts, where the fingers can hardly slip away (fig. 3b). Analyzing each point of the selected contour parts systematically the system tries to find a set of three contour points F_1, F_2 and F_3, whose normals are directed to one point (indicated by the white lines in fig. 3). The respective optimum gripping positions are connected by their grasp triangle indicated by the black lines in fig. 3. In addition to this obligatory condition for gripping positions the forces to be applied between the fingers have to compensate each other in the grasp plane in order to establish a stable grasp without a yawing torque. For raising the top of the camcorder cabinet it is additionally necessary that the forces $\mathbf{f}_i$ (cf. fig. 4) are high enough to compensate the gravity force $\mathbf{f}_g$ by contact friction forces $\mu\mathbf{f}_i$:

$$\sum_{i=1}^{3} f_{ix} = 0, \quad \sum_{i=1}^{3} f_{iy} = 0, \quad \mu \sum_{i=1}^{3} \mathbf{f}_i = \mathbf{f}_g \qquad (1)$$

Due to the fact that some object information like the friction coefficient μ and the gravity force $\mathbf{f}_g$ cannot be determined visually, the planned finger forces have to be scaled (up to now on the basis of default values given by the context). In case of excentric grasping (fig. 4) manipulation is destabilized by the torque ${}^G\mathbf{m}$, which can be also planned offline and independently of μ:

$$ {}^G\mathbf{m} = {}^G\mathbf{r}_S \times \mathbf{f}_g + \frac{\sum_{i=1}^{3} {}^G\mathbf{r}_i \times \mathbf{f}_i}{\sum_{i=1}^{3} \frac{|\mathbf{f}_i|}{|\mathbf{f}_g|}} \qquad (2)$$

For this reason the planning system estimates forces and torques by information about the object contour and its mass in order to provide reference values for force/torque controlled grasping.

Apart from these data necessary to perform stable manipulations the system plans the reference position and orientation of the gripper center ${}^T\mathbf{x}_G$ indicated by frame [G] in fig. 3, as well as fingertip positions F_1, F_2, F_3, respectively, enabling the robot to execute a coordinated hand-arm motion.

4 Hand-Arm-Coordination

Integrating a dexterous multi-fingered robot hand into a hand-arm-system leads to a highly redundant robot system. Therefore hand-arm-coordination is necessary in order to find a solution for the redundancy existing within the hand-arm-system and moreover, to take into account the special capabilities of the subsystems hand and arm. Usually the motion capabilities of hand and arm are quite different. While the hand can move only small translational distances, the arm compared to it has long ranges. However, carrying out the rotation of an object is easy by using the hand only, because the arm needs a lot of free space due to its large wrist movements. Such motions are often not desired or not possible, for example if there is an obstacle in the workspace. The coordination approach [Paetsch and Weigl 93] used within this hand-arm-system is perfectly working in cartesian space considering hand and arm as cartesian subsytems. By that means the complexity of the problem is reduced considerably. Furthermore, the cartesian coordination parameters are easily interpretable and very illustrative in the sense of system attitude and behaviour in contrast to parameters of joint based approaches. The basic scheme of the hand-arm-coordination is shown

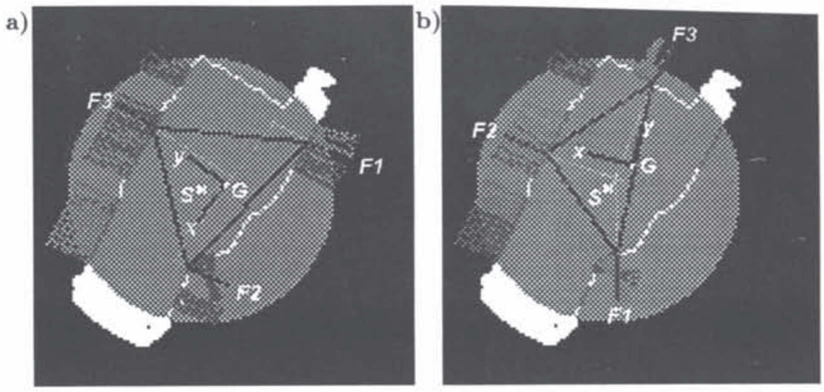


Fig. 3. The analysis of the object contour results in a palmar fingertip grasp (a) or a circular fingertip grasp (b) dependent on specifications due to the grasp situation. The circular grey area illustrates the accessible gripper work space.

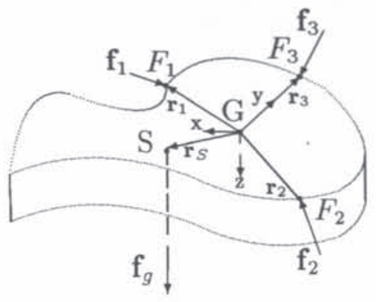


Fig. 4. Forces and torques acting on an object to be grasped by a three-fingered gripper.

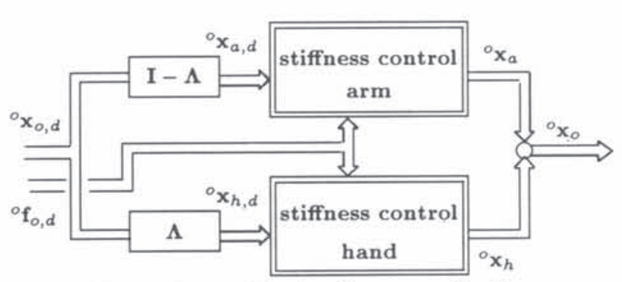


Fig. 5. Basic scheme of the hand-arm-coordination.

in fig. 5. A desired object motion, defined by a generalized six-dimensional position vector $^o\mathbf{x}_{o,d}$ in object coordinates (indicated by the superscript 'o' for the reference frame), is divided into two separate desired cartesian motions for the hand $^o\mathbf{x}_{h,d}$ and the arm $^o\mathbf{x}_{a,d}$ using a parameter matrix $\mathbf{\Lambda}$ determining the amount of motion to be carried out by the subsystems respectively:

$$^o\mathbf{x}_{h,d} = \mathbf{\Lambda}\, ^o\mathbf{x}_{o,d} \tag{3}$$

and

$$^o\mathbf{x}_{a,d} = (\mathbf{I} - \mathbf{\Lambda})\, ^o\mathbf{x}_{o,d} \tag{4}$$

with $\mathbf{I}$ as the unity matrix and $\mathbf{\Lambda}$ as a (6×6) diagonal parameter matrix:

$$\mathbf{\Lambda} = \mathbf{diag}(\lambda_x, \lambda_y, \lambda_z, \lambda_\varphi, \lambda_\vartheta, \lambda_\psi) \tag{5}$$

The respective motions of hand and arm are realized by the well-known stiffness control [Salisbury 80] used for each subsystem in order to find a solution to the joint angles for given cartesian values (even in case of redundancy) and to include a force/torque control of the complete system. For force measurement and computation the torque sensors of the gripper joints are available as well as a wrist force/torque sensor (not being used up to now).

Additionally the basic coordination scheme is extended by a supervision system for the feasibility of the computed hand and arm motions. This system stops the motion of a subsystem according to a certain criterion (in this case the joint limitations), and the remaining object motion is then automatically carried out by the other subsystem, as far as possible, in order to realize the desired object motion completely [Paetsch and Weigl 93].

5 Disassembly strategies

With this coordination approach the specific capabilities of a hand-arm-system can be used for complex tasks, e.g. assembly and disassembly. disassembly strategies based on the actual object forces and torques, described by the generalized six-dimensional force vector $^o\mathbf{f}_o$, can be easily included within the coordination scheme by a feedback loop

$$^o\mathbf{dx}_{o,strategy} = {^o}\mathbf{K}_{c,o}^{-1}\, ^o\mathbf{f}_{strategy} \tag{6}$$

as shown in the extended diagram in fig. 6. The desired stiffness behaviour of the object is defined by the (6×6) diagonal stiffness matrix $^o\mathbf{K}_{c,o}$ resulting from the stiffness matrices $^o\mathbf{K}_{c,h}$ and $^o\mathbf{K}_{c,a}$ for hand and arm as follows:

$$^o\mathbf{K}_{c,o}^{-1} = {^o}\mathbf{K}_{c,h}^{-1} + {^o}\mathbf{K}_{c,a}^{-1} \tag{7}$$

because the hand-arm-system can be modelled by two serially connected six-dimensional springs.

For the first disassembly experiments only two simple strategies $\mathbf{f}_{strategy} = (\ \mathbf{f}_s^T\ \mathbf{m}_s^T\ )^T$ for tautening one cable have been included. Therefore a strategic force $\mathbf{f}_s$ dependent on the measured force $\mathbf{f}_o$ has to be computed to move the object until a desired force $\mathbf{f}_{taut}$ is achieved:

$$\mathbf{f}_s = \mathbf{P_1}\,(\mathbf{f}_{taut} - \mathbf{f}_o) \tag{8}$$

Additionally, in order to compensate rotational deflections, that will be produced by the stiffness control due to the torque $\mathbf{m}_o$ caused by the tautened cable, an opposing torque $\mathbf{m}_s$ is computed:

$$\mathbf{m}_s = \mathbf{P_2}\, \mathbf{m}_o \tag{9}$$

The (3×3) diagonal parameter matrices $\mathbf{P_1}$ and $\mathbf{P_2}$ determine the magnitude of the strategic forces and torques.

6 Task Description

As a first step of disassembly solutions for grasping the top of the camcorder cabinet in order to separate it from its base are demonstrated by results of the following elementary operations documented by fig. 7: A coarse visual localization of the objects in the scene allows robot motion sequence planning and preshaping of the gripper as well as distribution of hand and arm motions for a coordinated motion of the complete system. For this purpose the silhouettes of the different objects in the scene are separated from each other and geometric features characterizing object position and size are localized in at least two images taken from different camera locations during robot motion (fig. 8a). Guided by these 3-dimensional object features the robot moves the camera above the top face of the object in order to get an image optimally adjusted to the size of the object.

From this image suitable for fine object inspection local contour features within the grasp plane are extracted for planning good contact positions and forces (fig. 8b).

After grasp planning the z-axis of the hand base frame [H] (cf. fig. 1) is perpendicular to the grasp plane. In order to approach the object in z-direction for grasping, hand and arm are carrying out a coordinated motion until the hand base frame [H] is a certain small distance right above the planned reference frame [G] in the object and the gripper is preshaped according

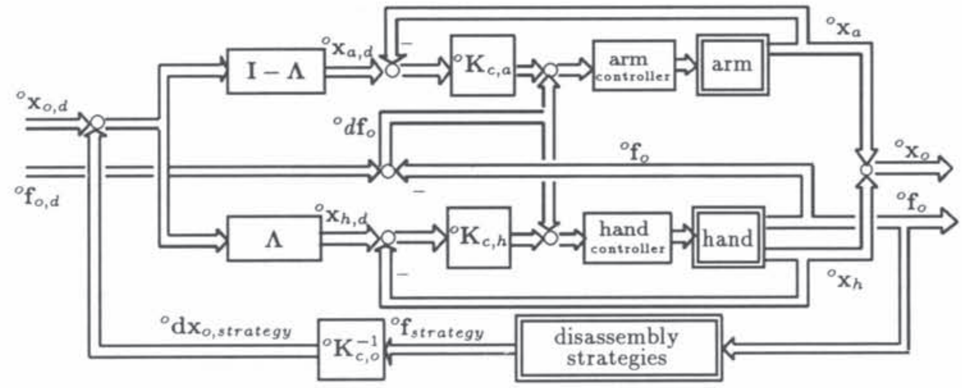


Fig. 6. Hand-arm-coordination scheme including disassembly strategies.

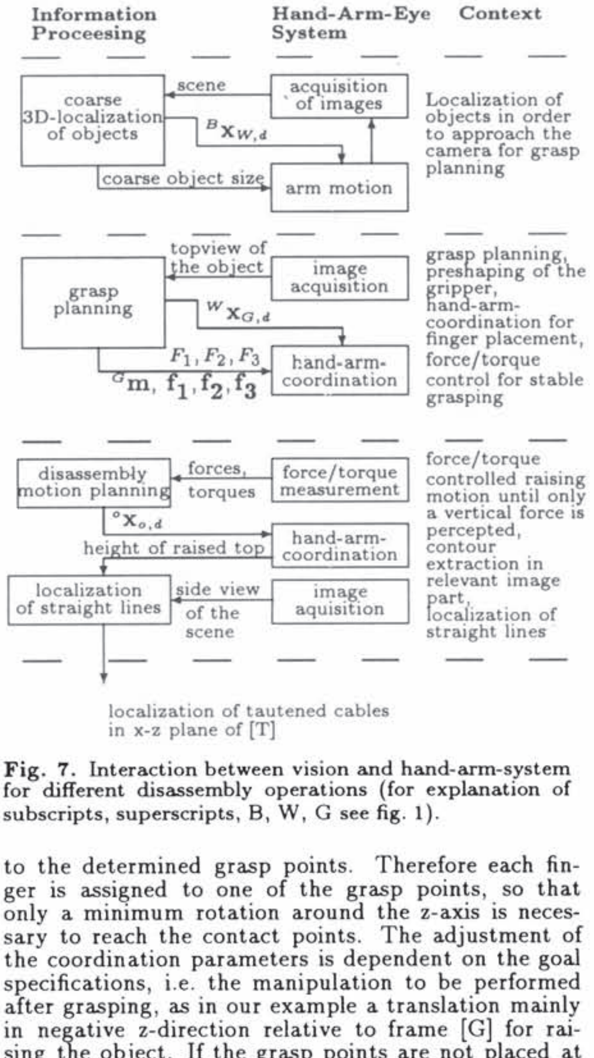
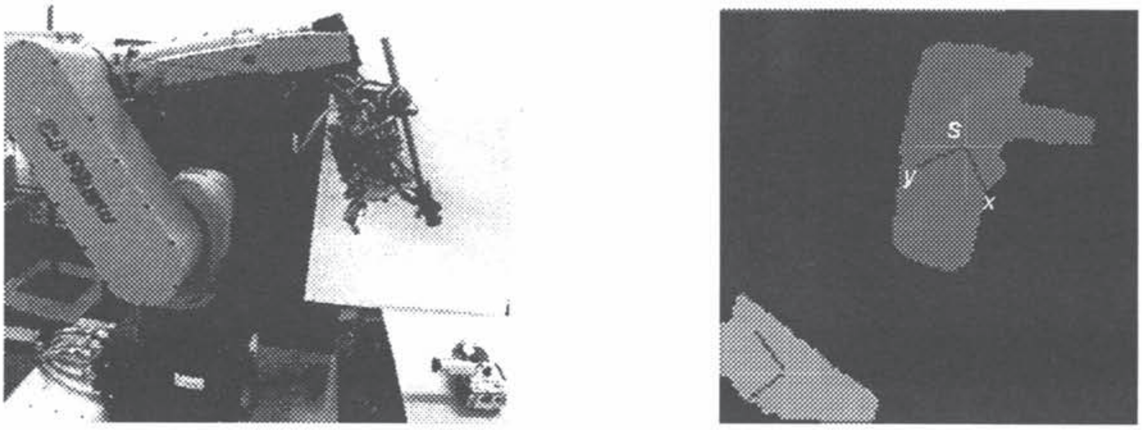


Fig. 7. Interaction between vision and hand-arm-system for different disassembly operations (for explanation of subscripts, superscripts, B, W, G see fig. 1).

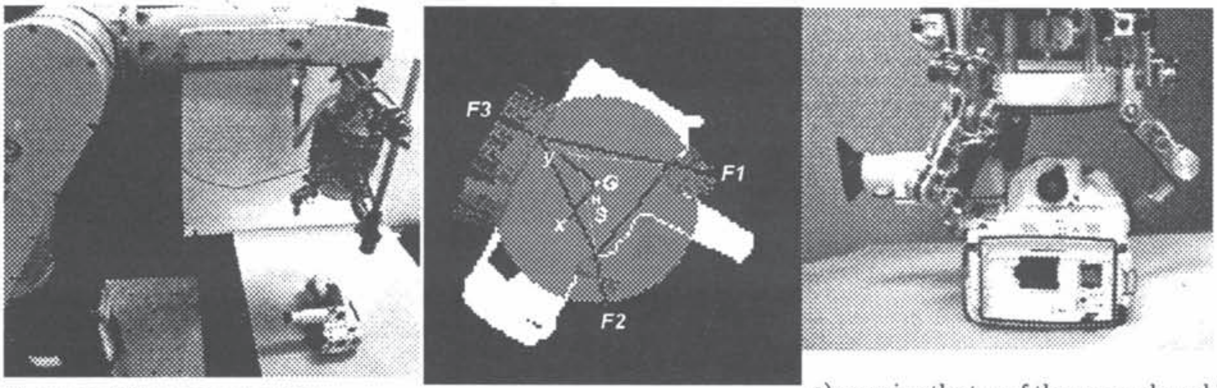
to the determined grasp points. Therefore each finger is assigned to one of the grasp points, so that only a minimum rotation around the z-axis is necessary to reach the contact points. The adjustment of the coordination parameters is dependent on the goal specifications, i.e. the manipulation to be performed after grasping, as in our example a translation mainly in negative z-direction relative to frame [G] for raising the object. If the grasp points are not placed at 120°-angles apart, a compensating hand-arm-rotation is carried out in order to provide maximum joint range availability for the first joints of each gripper finger (fig. 8c). Such optimizing motions in null space for further dexterous manipulations are possible by changing only the coordination parameters $\mathbf{\Lambda}$ without a given endeffector motion. After grasping the top of the camcorder cabinet it has to be raised without destruction of single parts requiring dexterous manipulations because the movement is constrained by various unmodelled cables connected to other parts inside the camcorder and tearing them off would cause damage to valuable modules and boards making re-use impossible. Hand-arm-coordination is used, again, to realize desired object motions and to change the system behaviour due to the requirements. For example, object translations are mainly carried out by the arm, while object rotations are mainly carried out by the hand. In addition to a given object motion the described disassembly strategies are applied as soon as an external force has been exceeded and thus, a disassembly motion is performed until exactly one cable is tautened and/or a maximum distance between the top and the camcorder base is achieved (fig. 8d). Usually this is the case if the cable is perpendicular to both parts of the camcorder cabinet and therefore we choose $\mathbf{f}_{taut} = (\,0,\,0,\,-f_{max}\,)^T$ (cf. eq. 8). By this strategy best accessibility is guaranteed for a second robot arm in order to cut off the visually localized cable, while the object position is fixed by the hand-arm-system. For visual localization of this cable by a scene camera previous localization results and information about the top of the camcorder cabinet available from the hand-arm-system are used to determine an image part in which only cables are present. Edge extraction in this image part allows the detection of straight lines as edges of minimum curvature (fig. 8e). These edges can be interpreted as the tautened cables because no other objects but cables exist in this image part between the camcorder cabinet and its top. Guided by these localization results a cutting instrument mounted on a second robot arm can be moved to the cable in order to disconnect the top of the camcorder from its base.

7 Experimental Results

The fundamental result of this paper is the realizability of disassembling the top of a camcorder cabinet under uncertain conditions using a dexterous hand-arm-system documented by the sequence of pictures in fig. 8. Nevertheless problems exist in the performance of some experimental steps. Due to inaccuracies in 3-dimensional object localization from a binary image sequence and the finite robot motion capabilities the mobile camera cannot always be moved exactly over the center of the camcorder so that sometimes not the entire grasp face is available for grasp planning. Employing wide-angle lenses would reduce the failure rate but is connected with the disadvantage of increased distortions and inaccuracies inadmissable for fine object inspection. So the use of lenses with variable focal length would be desirable. Moreover, it is sometimes difficult to find two initial camera positions for scene inspection in which the entire object is visible. Therefore it is recommendable to use a global camera mounted at the ceiling above the workspace to get an

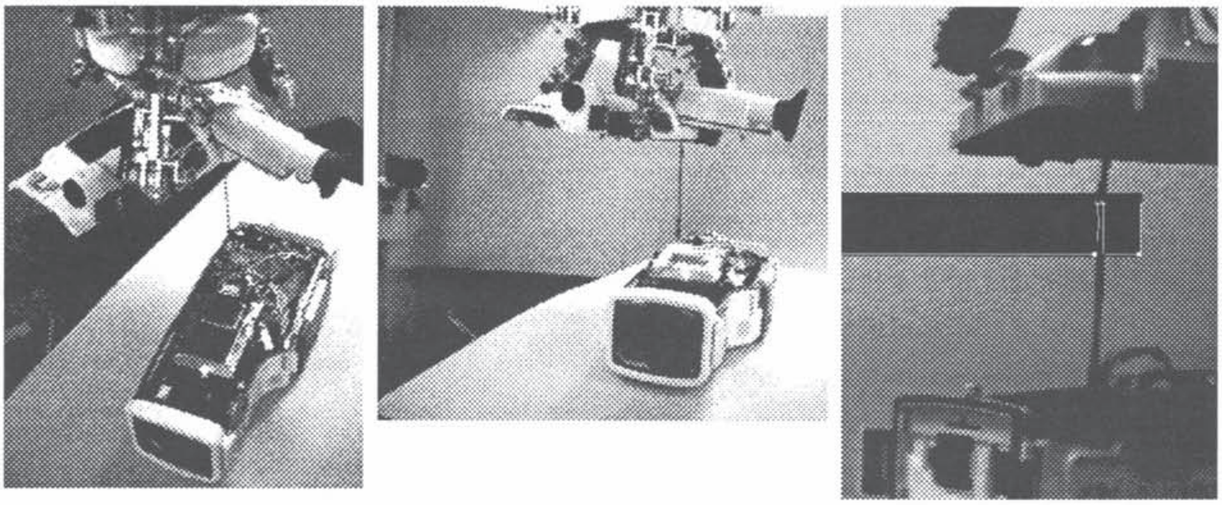


a) coarse visual inspection



b) approach for grasp planning

c) grasping the top of the camcorder cabinet



d) manipulation until cables are tautened

e) detection of tautened cables

Fig. 8. Illustration of the performed operations for disassembling the camcorder a) - e).

impression of rough planar object locations. Failures in the grasp planning process sometimes occur because variable resolution and visibility of the object due to different camera locations and lighting conditions lead to an insecure selection of contour areas favourable for grasping. Although the relatively inexact visual localization of contact points is not problematic because the gripper needs only coarse object information, the time consuming grasp planning process slows the disassembly motion down. Due to the special geometry of the employed gripper, whose fingers are arranged in 120°-angles apart, the palmar grasp planned in fig. 3a provides an insufficient joint range availability for further manipulations. Unfortunately the circular fingertip grasp shown in fig. 3b can also not be used because the contour part where finger 3 should contact the top of the camcorder is not accessible for grasping. So the accessible gripper work space has to be reduced by context specifications in order to exclude contour parts inaccessible for the gripper (cf. fig. 9). Very stable grasps can be performed, if the viewfinder, which is connected to the cabinet by a rotational joint, is moved out as demonstrated in fig. 9. Although this is a very stable configuration because fingers F_1 and F_2 are placed at strongly curved contour parts, where they can hardly slip away, the context prefers the grasp shown in fig. 8b due to manipulation requirements and the gripper geometry. This configuration provides highest flexibility because the contact points are arranged almost in 120°-angles apart and the adjustments of the joints necessary to establish the planned grasp are a minimum. Such suitable grasps are selected by a quality measure evaluating the equality of the distances of the determined gripping positions. Some-

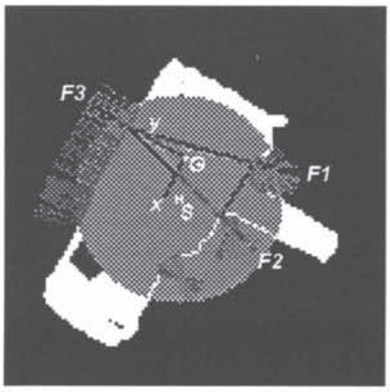


Fig. 9. Stable finger placement in strongly curved areas.

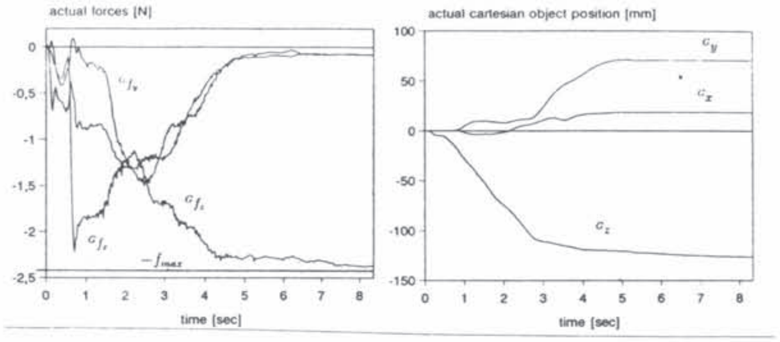


Fig. 10. Actual force and object position during the disassembly motion including strategies.

times grasping the top of the camcorder cabinet fails due to practical problems concerning the gripper geometry and design. Grasping such a large object compared to the gripper working space causes problems because the arrangement of the fingers does often not supply enough joint range availability for dextrous manipulations. Furthermore the smooth surfaces of the fingertips slip off the relatively small contact face at the object especially if external forces act due to tautened cables, for example.

An important aspect is torque compensation during grasping the object. In spite of the inexact visual determination of roll and nick torques caused by gravity a compensation stabilizes grasping as well as the disassembly operations as proved by the horizontal posture of the grasped camcorder top in fig. 8d. But experiments showed also that yawing torques may show up between the fingers although the planning system generated contact points and forces in order to prevent a yawing torque, theoretically. This can be explained by the fact that the fingers cannot be placed exactly due to the visual settings. If their lines of direction did not intersect in one point relatively high yawing torques appeared.

Fig. 8d and 8e demonstrate that the disassembly strategies work satisfactorily but they have to be extended in order to handle more than one cable. Fig. 10 shows the graphical representations of actual forces and object position during the disassembly operation to tauten a cable.

8 Conclusion

Experimental results document that disassembly even under uncertain conditions can be realized by using a coordinated complex hand-arm-eye system. The paper suggests a system architecture and shows by first experiments that the experimental system basically works although its quality has to be improved still.

Simple image processing can be used for visual inspection but complex planning processes have to be spent to achieve stable grasping of unregularly shaped objects by a multi-fingered gripper. So whenever possible, it is reasonable to perform grasp planning under stable camera, object and lighting relations before the disassembly motion starts. Grasping can be improved by applying less time consuming planning algorithms, more robust image processing and learning approaches to avoid parameter adjustments.

The advantages of a hand-arm-coordination could be utilized for grasping as well as for disassembly operations. So it seems reasonable to use this strategy for future applications in disassembly. Therefore future work will focus on the development of disassembly sequences and sensor based strategies in order to disassemble more parts out of the video camera recorder. Due to the complexity of the system a knowledge-base has to be developed for specification of context information.

Acknowledgement

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