A Force-Torque Sensor-Based Motion Strategy for Robot Assisted Disassembly

Alexandra Weigl and Karlheinz Hohm
Darmstadt University of Technology
Control Systems Theory and Robotics Dept.
D-64283 Darmstadt, Germany
e-mail: alex@irt2.rt.e-technik.th-darmstadt.de

Abstract

This paper presents a flexible force-torque sensor-based motion strategy for an autonomous robot system facilitating the disassembly of electronic products into separate modules avoiding destruction. The strategy does not require an exact model of the environment, and it is robust concerning state uncertainties. Only the disassembly direction but not the exact complex trajectory for disassembling a respective part is specified in advance, while the fine motion is planned online based on the external forces and torques arising during the disassembly operation. Besides the explanation of the underlying ideas, experiences and results from practical laboratory experiments document the efficiency and flexibility of the disassembly strategy for various applications.

1 Introduction

Due to environmental and economical reasons automated disassembly becomes an interesting problem and great challenge in automation. In consideration of the resulting quantity of products to be recycled in the near future and from the point of view of human and safe working conditions for human beings, the automation of disassembly processes seems to be indispensable. Moreover, the productivity and re-usability can be improved considerably by automation. Therefore, future applications in automation should focus on robot assisted disassembly of a large variety of electronic products, for example, with the general aim to re-use valuable modules, sub-assemblies and components recovered from old products. Making re-use possible will not only increase the added value of recycling factories, but will also reduce the negative environmental impacts of end-of-life electronic products. In order to ensure the re-use possibilities, mostly non-destructive disassembly is necessary, as far as possible. However, this is a very difficult task requiring complex disassembly operations by highly sensorized and flexible robot systems (cf. [Weigl, 94], [Weigl and Seitz, 94], [Dario et al., 94a], [Dario et al., 94b]), because up to now only little attention has been paid to a product design meeting disassembly requirements. Due to the compressed structure of electronic products, for example camcorders, there is often a lack of clearance, so that the respective parts to be disassembled are hardly accessible and graspable.
In contrast to the widely held opinion, disassembly cannot be considered generally 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 occur due to aging, use or product repair. 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 (e.g. [Seitz et al., 95], [Weigl and Seitz, 94]. 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.
In contrast to many approaches to global disassembly planning, as for example methods for the generation of optimal product disassembly sequences (e.g. [Qian and Pagello, 94], [Subramani and Dewhurst, 91], [Homem de Mello and Sanderson, 89]), only a few direct approaches to robot assisted disassembly exist. But in most cases the real conditions are disregarded and the topic is restricted to rigid components and translational robot motions (e.g. [Woo and Dutta, 91]). The few general approaches for planning local disassembly fine motions are based on geometric reasoning only and require a large *a priori* knowlegde of the environment ([Wilson and Matsui, 92], [Zussmann et. al., 92]).
This paper presents a flexible force-torque sensor-based motion strategy for an autonomous robot system facilitating the disassembly of electronic products into separate modules avoiding destruction. The strategy does not require an exact model of the environment and is robust concerning state uncertainties.

In the next section the underlying ideas of the local disassembly strategy based on force-torque sensor information will be explained. Subsequently, the results from laboratory experiments documenting the efficiency and flexibility of the disassembly strategy will be presented in section three. Finally, some conclusions will be drawn and open questions will be discussed.

2 Local Disassembly Strategy

2.1 Payload Compensation

Fine motion planning for assembly or disassembly tasks is often based on external forces and torques. For this reason, a payload compensation is necessary in order to extract the external forces and torques from the force-torque sensor output $\mathbf{f}_s$ and $\mathbf{m}_s$. The wrist force-torque sensor of the robot is mounted between the robot tool plate and the end effector, which is a parallel-jaw gripper in our case (cf. fig. 1a). Therefore, the forces $\mathbf{f}_s$ and torques $\mathbf{m}_s$ measured by the force-torque sensor are not only the external forces $\mathbf{f}_{ext}$ and torques $\mathbf{m}_{ext}$ experienced by the end effector, but also additional forces and torques caused by the acceleration of the payload mass m due to gravity $\mathbf{g}$ and robot motion $\mathbf{a}$

$$\mathbf{f}_s = \mathbf{f}_{ext} + m(\mathbf{g} + \mathbf{a}) \qquad (1)$$

$$\mathbf{m}_s = \mathbf{m}_{ext} + \mathbf{r} \times m(\mathbf{g} + \mathbf{a}) \qquad (2)$$

where the payload mass m is the combined mass of the gripper and the grasped part in the gripper and $\mathbf{r}$ is the center of gravity.
The external forces $\mathbf{f}_{ext}$ and torques $\mathbf{m}_{ext}$, taken as the basis for the generation of the local disassembly fine motion, can be extracted from the sensor output $\mathbf{f}_s$ and $\mathbf{m}_s$ according to equation (1) and (2).
The graphic representations of the torques during a free rotational robot motion, i.e. no external forces and torques are acting on the end effector, are shown in figure 1 before and after the payload compensation. The payload mass m and its center of gravity $\mathbf{r}$ is composed of the respective parameters of the gripper, the sensor and the grasped object. While the mass and the center of gravity of gripper and sensor are either known or can be determined automatically in advance by a few selected simple robot movements, the mass and the center of gravity of the object to be manipulated are not always known in disassembly applications, so that in this case, an estimated value has to be used. Since the strategy to be presented in the following is very robust concerning uncertainties, also inaccuracies resulting from the determination of the external forces and torques by the payload compensation can be handled.

2.2 Sensor-Based Motion Strategy

Due to the raised uncertainty in disassembly it is recommendable to specify only the coarse path for disassembling a respective part in advance, while the sensor-based fine motion is planned online. The local

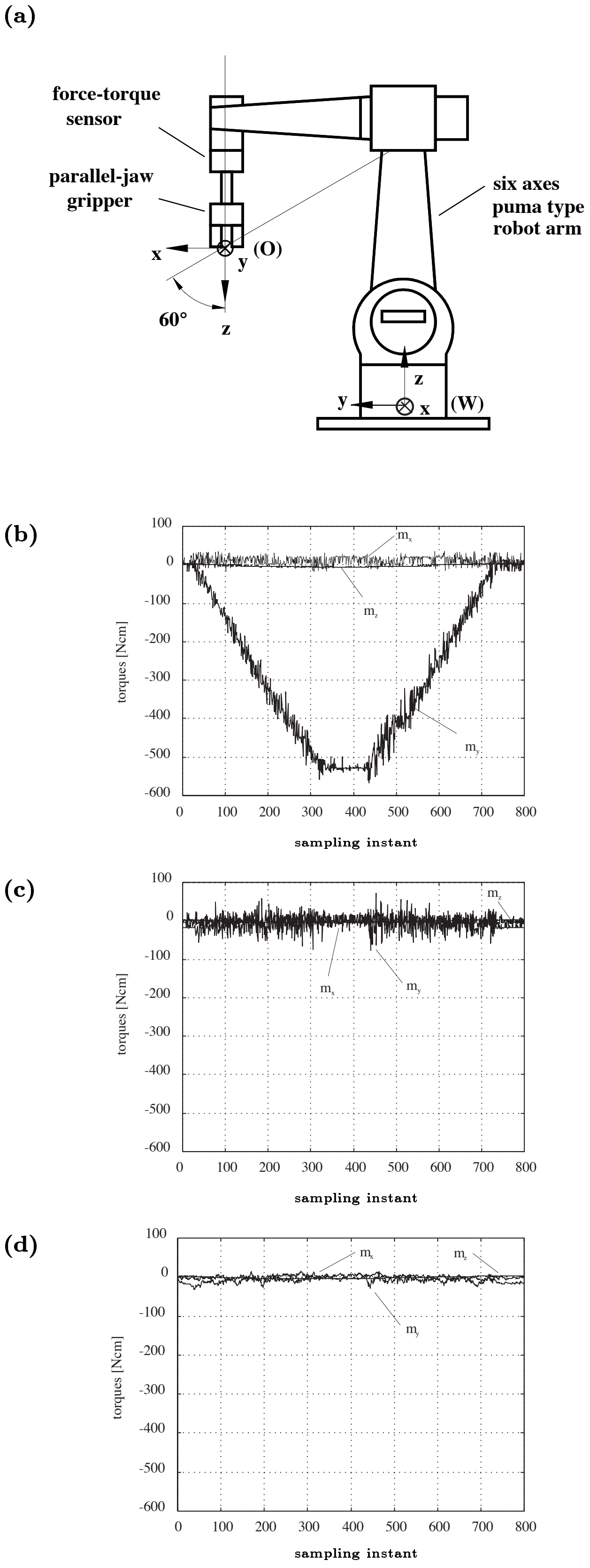

Fig. 1. Graphic representation of the torques during a free rotational robot motion of 60 degrees about the y-axis of the object coordinate frame (O) and back to the starting-position (a): torques measured by the sensor (b), torques after payload compensation (c), torques after payload compensation and filtering (d). The time interval between consecutive sampling intervals is 48ms.

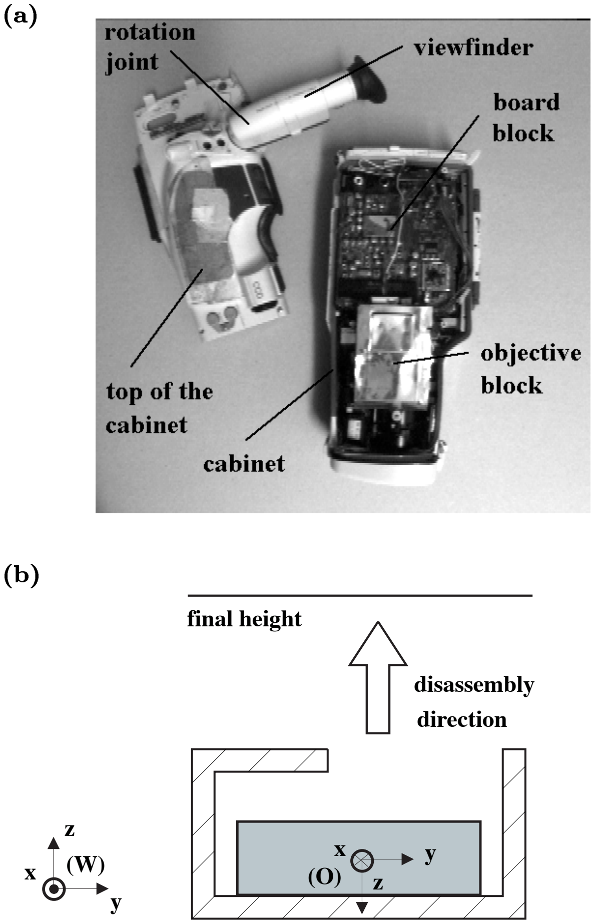

Fig. 2. A view inside the camcorder shows the initial location of the objective block to be disassembled (a). The disassembly motion upwards is constrained by some parts of the box, so that the disassembly strategy has to cope with this obstacle (b).

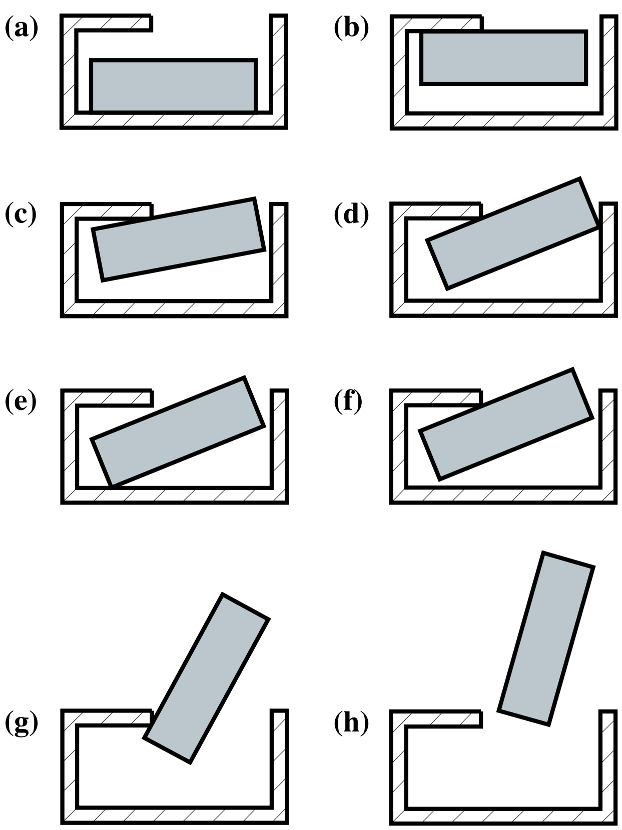

Fig. 3. The figures (a) – (h) represent a typical sequence of situations during the disassembly of the objective block out of a camcorder.

disassembly strategy developed in this work requires only little *a priori* knowlegde of the environment. Because not an exact complex disassembly trajectory is specified, but only the coarse disassembly direction, no exact model of the environment is necessary. In the following, the strategy will be illustrated by some representative example, the disassembly of the objective block out of a camcorder. The complex initial situation is shown in figure 2a and in a simplified schematic representation in figure 2b. The objective block is located in a box, which allows a disassembly motion upwards only. However, this motion is constrained by the undercut of the box, so that during the disassembly operation the strategy has to avoid the obstacle. A break-off criterion for a successful disassembly operation is passing a final height, which guarantees the complete removal of the part out of the box. Figure 3 represents a typical sequence of situations during the disassembly of the objective block out of a camcorder. The disassembly strategy has been developed imitating the human behavior. In the beginning (cf. fig. 3a), the part is moved in the disassembly direction (cf. fig. 2b), until this motion cannot be continued (cf. fig. 3b), because an obstacle, in this case the undercut of the box, is detected by the measured forces and torques resulting from the one-sided contact. The reaction to the torque is an object rotation (cf. fig. 3c), while the original disassembly motion, i.e. the upward movement of the object, is continued, which leads to the situation shown in figure 3d. The second contact with the boundary on the right side results in the wedging of the object. Even if the object orientation is changed, the disassembly motion upwards cannot be continued in this case. The original disassembly motion has to be stopped and the part has to be moved down again a little bit (cf. fig. 3e). By this evading movement forces and torques are avoided. As soon as the object is freely movable again, the disassembly motion upwards is tried once more leading to the situation represented in figure 3f. Now, a succession of the situations shown in figure 3c–f follows, until the object can be removed (cf. fig. 3g). Finally, it is possible to lift the part up to the final height (cf. fig. 3h). This way of acting corresponds to the behavior of a blindfolded human being. Since the robot is not equipped with a vision system, its situation is comparable. But of course, the human tactile sensing is much more sensitive. Moreover, human beings can refer to their experiences in solving problems and they are able to learn.

Derived from the behavior described above, essentially four rules for the disassembly motion control of the robot can be stated:

R1: **IF** the object is freely movable and experiences no forces and torques, **THEN** move the object in the disassembly direction:

$$\mathbf{v} = \mathbf{v}_{disassembly} \tag{3}$$

R2: **IF** the object is movable and experiences small forces and/or torques, **THEN** avoid forces and torques by evading movements but without stopping the original motion in the disassembly direction:

$$\mathbf{v} = \mathbf{v}_{disassembly} + \mathbf{v}_{evading} \tag{4}$$

R3: **IF** the object is movable and experiences large forces and/or torques, **THEN** stop the original motion in the disassembly direction and avoid forces and torques by evading movements:

$$\mathbf{v} = \mathbf{v}_{evading} \tag{5}$$

R4: **IF** the object is stuck and not moveable at all, **THEN** execute randomly evading movements, e.g. search all over the possible degrees of freedom, vibrating motions etc.:

$$\mathbf{v} = \mathbf{v}_{random} \tag{6}$$

where $\mathbf{v} = (v_x, v_y, v_z, \omega_x, \omega_y, \omega_z)^T$ is the six-dimensional vector of the nominal translational and rotational velocities for the robot generated by the local disassembly strategy. Usually, the given disassembly velocity $\mathbf{v}_{disassembly}$ is constant in the world coordinate frame (W) and a disassembly direction is specified only, i.e. for the upward movement in z-direction (cf. fig. 2b) with the velocity v follows:

$$^{w}\mathbf{v}_{disassembly} = (0, 0, v, 0, 0, 0)^T \tag{7}$$

Generally, the velocity $\mathbf{v}_{evading}$ of the evading movement generated by the strategy is proportional to the difference of the nominal external forces and torques $^{o}\mathbf{f}_{ext,nom}$ and the actual external forces and torques $^{o}\mathbf{f}_{ext} = (f_{ext,x}, f_{ext,y}, f_{ext,z}, m_{ext,x}, m_{ext,y}, m_{ext,z})^T$ in object coordinates

$$^{o}\mathbf{v}_{evading} = \mathbf{K}_R \left(^{o}\mathbf{f}_{ext,nom} - ^{o}\mathbf{f}_{ext}\right) \tag{8}$$

$\mathbf{K}_R$ is a (6×6) diagonal parameter matrix, which can be different for rule R2 and R3.

During the disassembly motion jamming and wedging of the part to be disassembled have to be overcome. Particularly, figure 3d shows a situation of jamming, in which the object is stuck and rule R4 is applied. According to the human behavior, first of all, a careful search all over the possible degrees of freedom is carried out. If this is not successful, randomly vibrating motions reducing the coefficient of friction are executed. Random evading movements can be applied also in the case of not interpretable sensor data. Randomization has been proven to be an useful primitive in the solution of robot tasks, because the class of solvable tasks is increased, the knowledge requirements of the strategies are reduced and the planning and execution process is simplified (cf. [Erdmann, 90].)

After implementing the disassembly strategy, various laboratory experiments have been carried out. The respective experimental results will be presented in the next section.

3 Experiments

Besides the problem of disassembling a block out of a box (cf. fig. 3), furthermore, the disassembly of two different electronic products, a camcorder and a PC, has been investigated. The disassembly strategy has been applied to several disassembly tasks with high success rates (cf. table 1). The error rate of 4% for the disassembly of the objective block out of the camcorder does not result from the disassembly strategy itself but mainly from grasping problems, e.g. if the grasp is not stable enough, the object is slipping and in the worst case, the gripper loses the object. Figures 4 und 5 show the external forces and torques and the nominal velocities generated by the strategy during the disassembly of the objective block out of the camcorder. Besides the oscillating translational motions of the object in y- and z-direction respectively (cf. v_y and v_z in figure 4), mainly an object rotation about the x-axis (cf. ω_x in figure 5) is generated by the disassembly strategy. After 600 to 650 sampling instants the objective block has been disassembled and is then transferred to the final height.

During the different disassembly experiments it has been shown, that due to the disassembly strategy only slight jamming and wedging of the object to be disassembled occurs. Therefore, evading movements for situations, in which the objects are stuck, as described in rule R4, such as searching all over the possible degrees of freedom or executing randomly vibrating motions, are hardly often necessary. Because by applying rules R1 to R3, the object to be disassembled is permanently in motion and this restlessness prevents the objects from hard jamming and wedging or being stuck.

In addition to the disassembly of the camcorder another experiment has been carried out in order to prove the efficiency of the motion strategy regarding the problem of jamming and wedging. This has been the disassembly of a printed circuit board out of a PC, which is in a sloping position (cf. fig. 6). Also in this case the success rate was 100% for 100 trials. During this experiment the disassembly strategy generates an oscillating motion similiar to the behavior of a human being removing a printed circuit board out of the card-slot.

Depending on the context, by modifying the respective strategy parameters, such as the velocity in disassembly direction $\mathbf{v}_{disassembly}$, the velocities for the evading movements $\mathbf{v}_{evading}$ in each cartesian degree

disassembly object	number of trials	success rate [%]
viewfinder cabinet	50	100
top of the cabinet	50	100
small board in the top of the cabinet	50	100
objective block	100	96

Table 1. Results of the various disassembly experiments for the camcorder (cf. fig. 2).

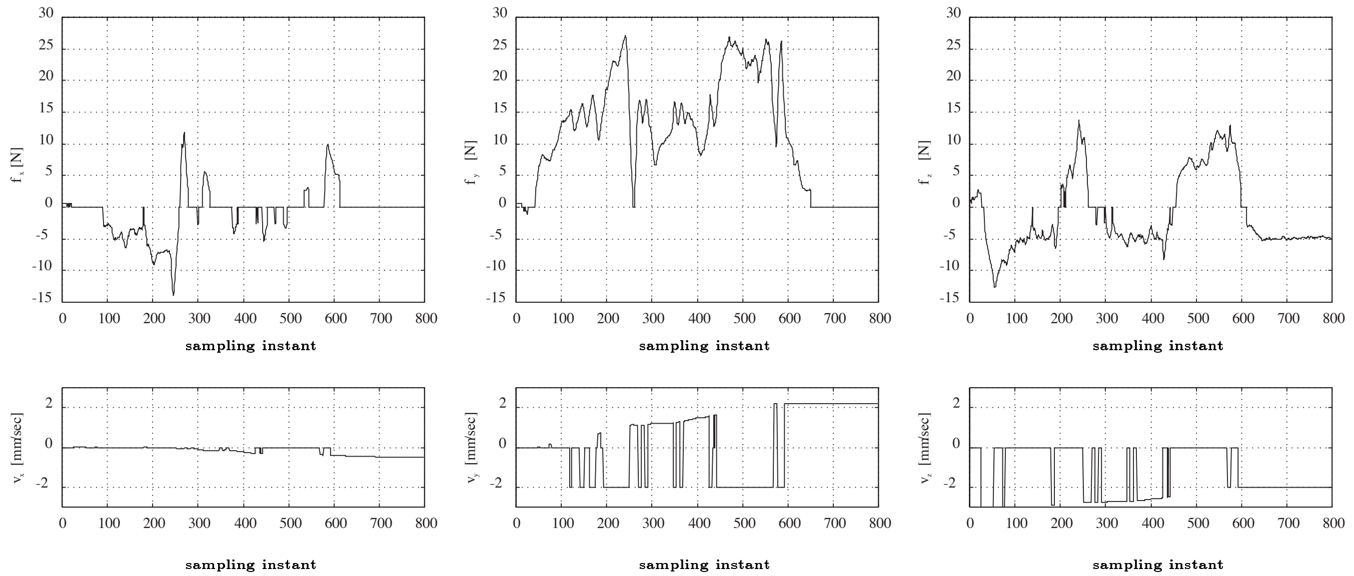

Fig. 4. Graphic representation of the external forces $\mathbf{f}$ and the nominal translational velocities $\mathbf{v}$ in x-, y- and z-direction in object coordinates (O) generated by the strategy during the disassembly of the objective block out of the camcorder (cf. fig. 2b). The time interval between consecutive sampling intervals is 48ms.

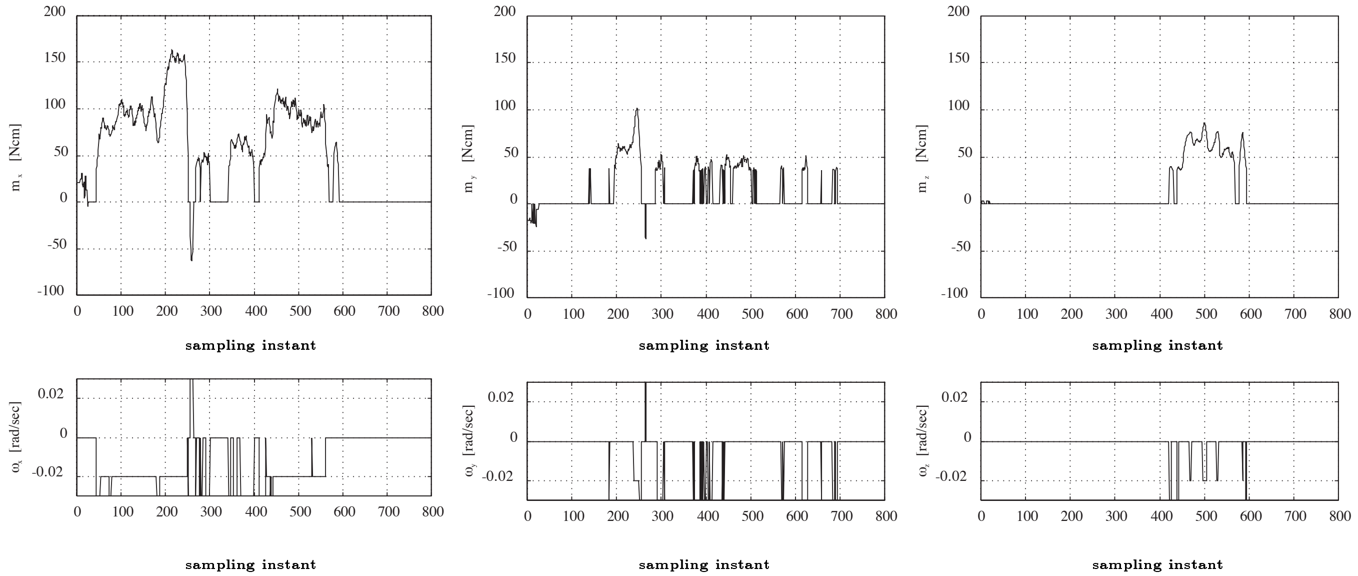

Fig. 5. Graphic representation of the external torques $\mathbf{m}$ and the nominal rotational velocities $\boldsymbol{\omega}$ about the x-, y- and z-axis in object coordinates (O) generated by the strategy during the disassembly of the objective block out of the camcorder (cf. fig. 2b). The time interval between consecutive sampling intervals is 48ms.

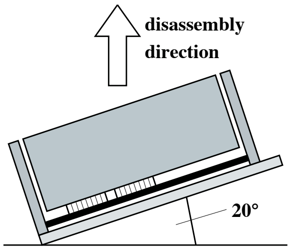

Fig. 6. Set-up for disassembling a printed circuit board of a PC out of its card-slot. In order to prove the efficiency of the strategy concerning jamming and wedging, the PC is in a sloping position of 20 degrees, but the given disassembly direction is straight upwards.

of freedom, the nominal external forces and torques $\mathbf{f}_{ext,nom}$, the threshold values for the forces and torques etc., the disassembly behavior and time can be improved for the different objects and tasks. For example, while for disassembling the objective block out of the camcorder small threshold values for the forces and torques have been used in order to avoid damage and destruction, however, the disassembly of the PC board out of its card-slot has to be carried out with higher nominal forces and torques and higher threshold values in order to get it out of its socket (cf. fig. 6). The integration of user knowlegde and experience for different disassembly tasks can be facilitated and improved by a fuzzy man-machine interface.

4 Conclusion

A local sensor-based disassembly strategy has been developed, which allows the disassembly of electronic products into separate modules avoiding destruction. Experimental results document that the strategy basically works. Furthermore, its efficiency and flexibility has been proved for various applications. The fine motion planning is based on the external forces and torques arising during the disassembly operation. As demanded in the beginning, the strategy does not require an exact model of the environment. Instead of planning an exact and complex disassembly trajectory in advance, only the coarse disassembly direction has to be specified. Moreover, the strategy is robust concerning state uncertainties and also able to overcome jamming and wedging.

Because this sensor-based disassembly strategy is only a local strategy, it is not able to handle all possible situations. In case of a dead end, for example, the strategy will probably fail. For this reason, additionally, a global strategy on a higher planning level has to be developed in order to adapt the given disassembly direction, if necessary. Furthermore, additional strategies for learning parameter adaptation and online modification could be useful also.

For implementing the four rules of the disassembly strategy the respective threshold values for the forces and torques have to be determined. With regard to an easy man-machine interface, therefore, in a next step the application of a fuzzy approach will be investigated. Moreover, the advantage of a fuzzy controller is the smooth transition between the different situation clusters. Considering disturbances involved in measured force-torque data by fuzzification of the measured values and corresponding determination of the membership functions, an additional filtering of the force-torque data, always causing time delay, is not necessary and the system reacts promptly to the sensor information.

For future work flexible strategies to approach the objects to be disassembled and the referring gripping positions have to be developed. This is a very difficult problem, because the respective parts are hardly accessible and graspable. A suitable grasping strategy based on tactile dexterity will be developed similiar to the local disassembly strategy by adapting the motion rules.

Finally, the different solutions have to be integrated into an overall planning system in order to select, to control and to supervise the necessary strategies for the respective disassembly tasks.

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