Disassembly Planning using Visual Servoing

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Abstract: The paper presents a disassembly algorithm which computes the cost required for the automatic disassembly of a component of a product. The product is modelled using a hierarchical model that represents the relations among components. The characteristics of the product are expressed using matrices, which represents the hierarchical model and the cost of removal the unions among components. The disassembly cost of a component is computed taking the trajectory required to perform the separation of a component into consideration. This trajectory is performed using an image-based visual-servoing system. To determine the cost of these trajectories the concepts of manipulability and perceptibility are employed.

1 INTRODUCTION

Product disassembly is one important issue in today industry. The disassembly of products can be performed for recycling its components or for maintenance tasks where the products are disassembled to arrive to the defective component and then replace it and finally re-assembly the product to its original status.

The product can be represented in different ways. A hierarchical model of the relations among components is used by Xia et al., 2012; Puente et al., 2010 and Torres et al., 2003. An AND/OR graphs are used by authors like Ma et al., 2011. A connector-knowledge-based approach is used by Li et al., 2010.

The use of robots to perform these tasks allows greater flexibility in the systems and obtaining a good quality in this task. That is the reason that in this paper a robot arm is considered to perform the disassembly tasks.

One point to take into consideration is the cost of the disassembly. The product can have several options to achieve the desired component, and these options not only include the removal of different components, they include the use of different tools for each task, as well as the possibility of using different tools for the same tasks.

In order to perform the disassembly of the product a robot visually guided is employed. Nowadays, the visual servoing systems are a well-known approach to guide a robot using image features (Chaumette and Hutchinson, 2006). This works employs image-based visual servoing which concerns the problem of using image information directly to control the robot motion. In order to determine the disassembly sequence it is worth considers, not only the properties of the product to be disassembled, but also the fact that the components of the product will be removed by using a robot visually guided.

The paper is structured with the following sections. In Section 2, the computing of visual servoing cost is presented. In Section 3, the disassembly algorithm is described. Finally the conclusions are presented.

2 VISUAL SERVOING COST

In Yoshikawa 1985, the concept of manipulability is defined as the distance of any redundant configuration from singular ones. The robot cannot be moved in any direction of its workspace when the robot is in a singular configuration. At this moment, the manipulability is annulled. However, when the manipulability is non-zero, the robot-end can be displaced in any direction of the workspace. Higher manipulability implies the robot achieves a dexterous configuration staying clear of singularities. Therefore high manipulability is desired during the disassembly. The manipulability,

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can be obtained by equation 1.

$$\omega_r = \sqrt{\det\left(\mathbf{J}_r^T \mathbf{J}_r\right)} \quad (1)$$

where $\mathbf{J}_r$ is the robot Jacobian which relates the velocity of the robot end-effector $\dot{\mathbf{r}}$ and the joint-space velocity $\dot{\mathbf{q}}$, see equation 2.

$$\dot{\mathbf{r}} = \mathbf{J}_r(\mathbf{q})\dot{\mathbf{q}} \quad (2)$$

Related with the robot manipulability is the concept of robot perceptibility (Sharma and Hutchinson 1997). Perceptibility provides a quantitative measure of the ability of a camera to observe the changes in image features due to relative motion. When the perceptibility is low, the vision system cannot perceive the motion along a given direction of the workspace. Therefore, a high value for the perceptibility is also required. Perceptibility is defined as the following scalar function of equation 3.

$$\omega_v = \sqrt{\det\left(\mathbf{L}_s^T \mathbf{L}_s\right)} \quad (3)$$

where $\mathbf{L}_s$ is the interaction matrix (Chaumette and Hutchinson, 2006).

As indicated in Sharma and Hutchinson 1997, in the case of a non-redundant robot, a composite measure can be obtained from manipulability and perceptibility using a weighted sum of both criteria (equation 4).

$$\omega = k_r \omega_r + k_v \omega_v \quad (4)$$

where k_v and k_r are constants that allow us to weight the relative importance of manipulability and perceptibility.

As it is previously indicated, a cost related with manipulability and perceptibility is computed and it is employed to determine the disassembly sequence. This cost is obtained from the trajectory described by the robot during the removal of a given component. The cost is obtained in two steps. Firstly, the required trajectory, ψ, is computed and, secondly, the cost is determined from the previous determined trajectory $\mathbf{C}_{rv}(\psi)$.

A visual servoing task can be described by an image function, $\mathbf{e}_t$, which must be regulated to 0 (equation 5).

$$\mathbf{e}_t = \mathbf{s} - \mathbf{s}^* \quad (5)$$

where $s = (f_1, f_2, \ldots f_M)^T$ is a M x 1 vector containing M visual features observed at the current state ($f_i = (f_{ix}, f_{iy})$), while $\mathbf{s}^* = (f_1^*, f_2^*, \ldots f_M^*)^T$ denotes the visual features values at the desired state, i.e. the image features observed at the desired robot location.

In order to determine the trajectory, ψ, the desired image features, $\mathbf{s}^*$ and the corresponding positions with respect the object frame, $\mathbf{P}_P^O$, are obtained from the model of the component to be removed. The camera located at the robot-end must observe these features. When the robot achieves the location in which the extracted visual features, $\mathbf{s}$, are equal to $\mathbf{s}^*$, the robot will be in the correct location to perform the removal of the component.

The control action of equation 6 drives the eye-in-hand camera towards the desired location to perform the disassembly.

$$\mathbf{v}^C = -\lambda \mathbf{L}_s^+ (\mathbf{s} - \mathbf{s}^*) \quad (6)$$

where λ is a positive control gain and $\mathbf{L}_s^+$ is pseudo-inverse of the interaction matrix. In order to compute the trajectory, the value of $\mathbf{s}$ must be determined at each iteration. To do so, we consider that the intrinsic and extrinsic camera parameters at the beginning of the trajectory are known. The intrinsic parameters do not vary along the trajectory and the variation of the extrinsic parameters is computed using (6). Therefore, at each iteration, projecting the previous mentioned points, $\mathbf{P}_P^O$, using the camera parameters, the value of $\mathbf{s}$ can be easily obtained.

Once the trajectory required to perform the removal of the component is obtained, the composite value of manipulability and perceptibility, ω, is obtained at each point of the obtained trajectory. The value of $\mathbf{C}_{rv}(\psi)$ is finally computed by determining the lowest value of ω obtained during the trajectory.

Figure 1, Figure 2 and Figure 3 represents an example of computation of the cost $\mathbf{C}_{rv}(\psi)$. Figure 1 represents the trajectory described by the robot to perform the grasping of the component to be removed. This trajectory is obtained using visual servoing.

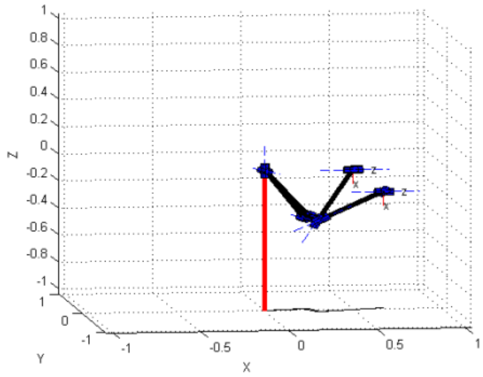

Figure 1: Initial and final robot configurations.

The evolution of the image features during the trajectory is represented in Figure 2.

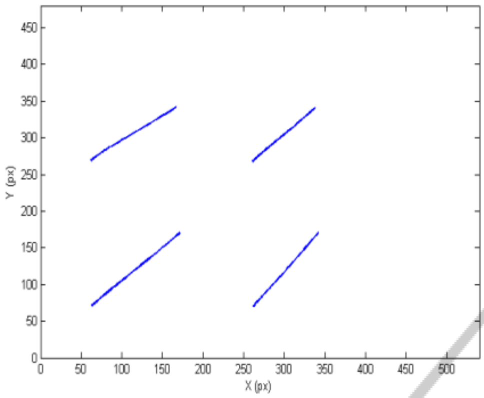

Figure 2: Trajectories of the image features.

Finally, the composite value of the manipulability and perceptibility is represented in Figure 3 ($k_r = k_v = 0.5$). As it is previously indicated, the cost function is the lowest value obtained in Figure 3 (in this case 0.056).

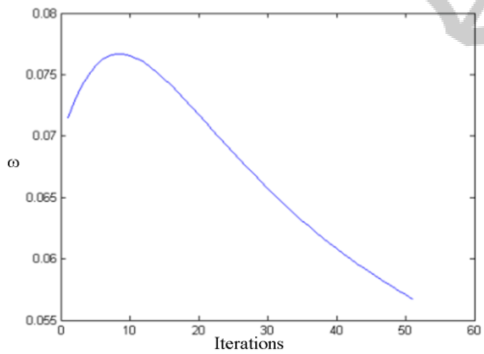

Figure 3: Composite value of the manipulability and perceptibility.

3 DISASSEMBLY ALGORITHM

The proposed algorithm is based on a previous research (Puente et al., 2010; Torres et al., 2003). This algorithm used a model of the product where the components have unions among them, and an assembly component can be represented as a group of sub-assembly components.

The novelties of the algorithm proposed are that it includes a matrix representation of the relationships among components and the visual-servoing cost to compute the best disassembly sequence. In this representation it takes into consideration different sequences for disassembling a component according to the tool used. The cost is based on the tool required, and the trajectory required to perform the separation of the component. Furthermore, the trajectory cost also includes the visual-servoing cost that takes into consideration the manipulability and perceptibility of the component. All this novelties allows optimizing the disassembly sequence of the components rescued.

Before describing the disassembly planning strategy, the notation that will be employed during the algorithm description is defined in table 1.

Table 1: Definition of algorithm parameters.

n	No. of components in the product.
v	No. of fasteners in the product.
w	No. of subassemblies in the product.
h	No. of tools for disassembly.
$\{c_1,c_2,\ldots, c_n\}$	Components that form the product.
$\{f_1,f_2,\ldots, f_v\}$	Fasteners that form the product.
$\{m_1,m_2,\ldots,m_w\}$	Subassemblies.They are combinations of components and subassemblies.
$\{t_1,t_2,\ldots,t_h\}$	Tools to disassembly of the product.
$U_{closure}$	Matrix of closure unions among components: ucl_{ij} = 1 if exists closure union between c_i and c_j; ucl_{ij} = 0 other case.
$U_{contact}$	Matrix of contact unions among components: uco_{ij} = 1 if exists contact union between c_i and c_j; uco_{ij} = 0 other case.
U	Matrix of unions. $U=U_{closure}+U_{contact}$; $u_{ij}=ucl_{ij}+uco_{ij}$
F	Fasteners matrix, which components are connected by a fastener: f_{ij} = 1 if the component c_i is joint with the fastener f_j; f_{ij} = 0 other case.
A	Matrix of assemblies: a_{ij} = 1 if the component c_i is part of the assembly m_j; a_{ij} = 0 other case.
$A_{fasteners}$	Matrix of assemblies and fasteners: af_{ij} = 1 if the fastener f_i is part of the assembly m_j; af_{ij} = 0 other case.
$A_{assemblies}$	Matrix of assembly assemblies: aa_{ij} = 1 if the assembly m_i is part of the assembly m_j; aa_{ij} = 0 other case.
C^i	Matrix of cost for tool t_i for component removal: c^i_{jk} = cost of removal the union between component c_j and component c_k with the tool t_i.
$C_{fasteners}$	Matrix of cost for fasteners removal: c_{ij} = cost of removal the fastener f_i with the tool t_j.

Taking into consideration the definitions of table 1, the minimum disassembly cost of a component can be computed following the next algorithm:

```
If $f_{dj}$=1 then
    Remove $f_j$
    $Cost_{min} += \min c_{jk} \; \forall k = 1 \dots h | c_{jk} > 0$
Endif
*If $u_{dj}$=1 then
    Remove $c_j$
    $Cost_{min} += \min c^{k}{}_{dj} \; \forall k = 1 \dots h | c^{k}{}_{dj} > 0$
Endif
If $a_{dj}$=1 then
   $a_{kj} = 0 \; \forall k = 1 \dots n$
   If $af_{kj} = 1$ then
        Remove $f_k$
        $Cost_{min} += \min c_{jk} \; \forall k = 1 \dots h | c_{jk} > 0$
    Endif
    If $aa_{jk} = 1 \; \forall k = 1 \dots w$ then
        If $af_{kj} = 1$ then
            Remove $f_k$
            $Cost_{min} += \min c_{jk} \; \forall k = 1 \dots h | c_{jk} > 0$
        Endif
        If $a_{lk} = 1$ then
          Remove $c_l$
          $Cost_{min} += \sum_{p=1}^{n} \min c^{m}{}_{pl} \; \forall m = 1 \dots h | c^{m}{}_{pl} > 0$
          Jump to * with d=j
        Endif
    Endif
Endif
```

The cost C^i is directly related with the visual servoing cost, $\mathbf{C}_{rv}(\psi)$, to following a trajectory to disassembly one component, due to that trajectory will vary depending of the tool used for removal the component.

4 CONCLUSIONS

This paper presents a method, which integrates information about perceptibility and manipulability in order to determine the sequence order in a disassembly process.

Taking the results obtained into consideration, the algorithm proposed could be used in real-time computation of disassembly strategies, giving flexibility to the system provided by the visual-servoing system.

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