Investigating Functionality: the case of Piercing Operation

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Abstract

The application of tools by artificial systems depends on the ability to recognize an object as having a particular function as well as on the ability to express the functional interaction. This paper focuses on the operation of piercing as means of investigating the issue of functional representation. The operation is expressed using a formalism based on Discrete Event System Theory (DES) and on the paradigm of Active Perception. The visual and tactile data acquired during piercing motor actions performed with a robotic manipulator is discussed.

1 Introduction

The recovery of the functionality of an object is a complex task. It requires the ability to gather data about the physical attributes of the object, to be able to reason about its applicability in a task, and to carry out a physical investigation to either validate the hypotheses or to gather additional information through exploratory procedures.

In the past, functionality has received limited attention,[4, 8, 3]. Recent systems,[7, 6, 2], have assumed, or addressed in a limited manner, the gathering of physical properties of an object. However, it seems that while the research is invaluable, it is important to deal with the recovery of these properties as well as to represent how the functional interaction takes place. In this paper, we focus on the interactive task component and in particular the functionality of piercing. A model of the operation based on DES [5] formalism is presented. It highlights the transitions among successive physical states of the procedure. A robotic manipulator equipped with a suitable tool was used for the experiments, and contact forces and torques as well as visual data were monitored in real-time in order to control the operation. Data is analyzed by the system so as to determine the current state, thus assessing the occurrence of piercing. Furthermore, examples are provided which show that a complete monitoring of the operation cannot be obtained if both tactile and visual information are not considered.

The paper is organized as follows: in section 2 the representation of functional interaction is introduced and the specific example of piercing is discussed. The experimental setup and typical data gathered during the experiments are shown in section 3. Discussion of the results and future work are provided in section 4.

2 Representing Interactions

Functionality of an object can be identified with its purpose and utility in a specific environment. Its purpose depends on the intention of an agent and the utility denotes its applicability in a particular task.

The tasks for investigating and expressing the functionality of a tool are expressed as Discrete Event Systems. The **states** correspond to some continua in the task evolution and the transitions between states are caused by **events**, representing the qualitative changes in environment or task evolution. The behavior of the system is characterized in terms of strings over some fixed alphabet Σ - set of events. Let the subset $L \subseteq \Sigma^*$ represent all event trajectories which are physically possible for the system. If **language** L is regular, there exists some finite automaton $\mathcal{G}$ such that L is generated/accepted by $\mathcal{G}$. This automaton $\mathcal{G}$ is a 5-tuple $\mathcal{G} = (Q, \Sigma, \delta, q_0, Q_m)$, where Q is the set of all possible states, Σ is the set of all possible events, δ is the transition function $\delta : \Sigma \times Q \rightarrow Q$, q_0 is the initial state, and Q_m is the subset of states called marker states.

The system consists of a *task supervisor* and models of various sensors which are characterized by the set of events they can observe. A task for expressing an interaction can be stated in terms of a language subject to controllability and observability requirements. A detail description is presented in [1].

2.1 Piercing: Functional Interaction

Piercing involves grasping an object (tool) at one end with the intention of bringing it to contact with a target object. Once the tool has been brought to contact, force must be applied to enable the tool to break the surface and penetrate the target object a given distance.

If the target object is elastic, then the position of the end-effector will have to be observed not only by force and position sensors but also by a vision sensor. It is only by means of observations through different sensory modalities that we are able to identify the behavior of the material. In particular, if the tool is partially elastic, both position and force sensor may assert events indicating that the tool is penetrating the target object whereas vision reveals a tool deformation.

Figure 1 shows a description of a piercing interaction. Some of the events, such as motion beginning and termination (α_1, α_{21}), are observable only by the

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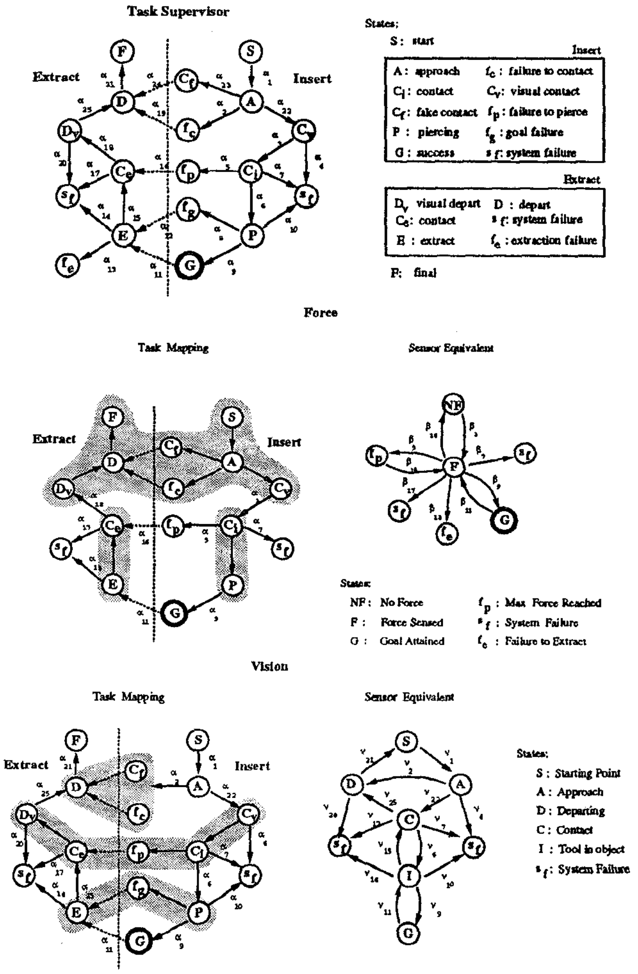

Figure 1: Mapping of piercing task (top) to vision, force and position sensors.

vision sensor while the event of reaching maximum force α_9 is observable only by the force sensor. Some of the states may become indistinguishable by a sensor modality. States $\{C_i,\ f_p,\ C_e\}$, $\{P,\ f_g,\ G,\ E\}$ and $\{D,\ f_c\}$ are indistinguishable by the vision sensor. Furthermore, some of the nodes do not map to any sensor for they identify only logical states in the task execution. However, the overall task is *piecewise observable*[1].

3 Experiments on Piercing

The experimental setup is illustrated in Figure 2. Two Puma 560 manipulators were used for the experiments. The first one performed the piercing operation by means of an aluminum tool mounted as end-effector. A wrist Lord Force/Torque sensor monitored resulting contact forces. The second manipulator was used for moving the vision system (a b/w camera) so as to provide a good observation point at any time.

Three time-varying signals were analyzed to evaluate how the operation was proceeding: the visual height of the tool, the force signal component orthogonal to the object surface, and the position of the end-effector. The visual height of the tool was determined in each image by thresholding, and the resulting time-varying signal was the input visual data to the system.

A set of different objects were used as a test-set for the experiments. The objects were made of different materials and they were chosen basically to test the system with varying degrees of material hardness and elasticity. Typical signals gathered during a piercing operations are shown in Figure 2.

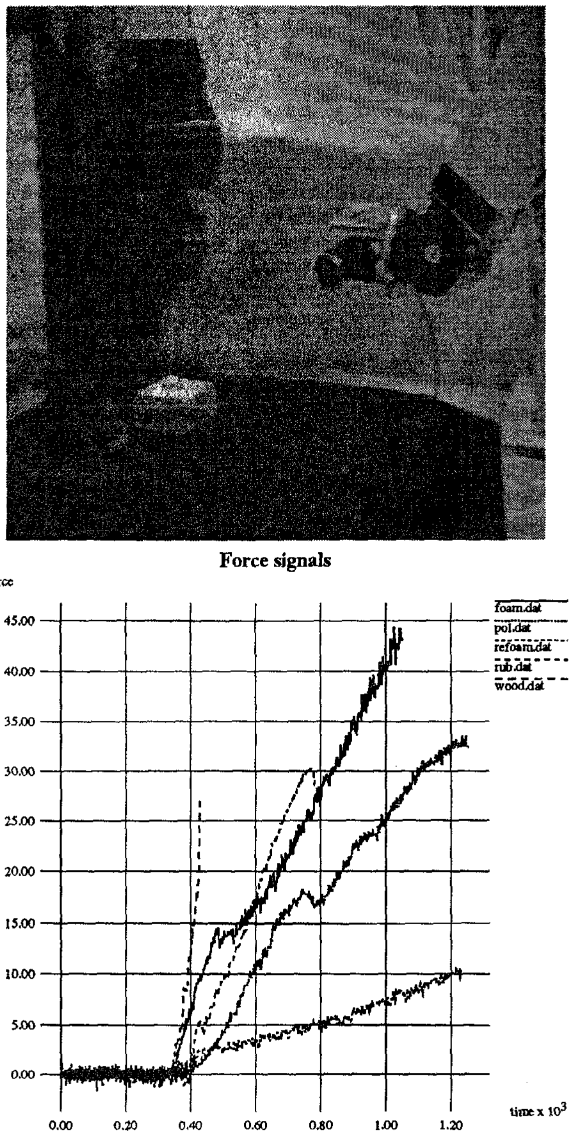

Figure 2: Top: Experimental Setup. Bottom: Force signals for different materials.

4 Results and Discussion

The force profiles for different materials in Figure 2, suggest that the observability of the piercing operation in the force domain can be associated with a sudden variation in the slope of the signal. Such variations occur in all the signals except in the cases of wood and sponge, which identify cases of failure in the operation.

In general, the position of the arm provided by the robot encoders can be used for determining the occurrence of piercing, if the height of the tool and the position of the object to pierce are assumed to be known *a priori*. However, if monitoring of piercing were to be performed only on the basis of these proprioceptive data, it would fail for non-rigid objects, where the arm can move further than the initial height of the object without penetrating it. Similarly, the height of the tool monitored by the visual system is a powerful cue for assessing if piercing is occurring. This is particularly true if the visual system is located in a vantage observing position, as in the case of the experiments described in this paper. However, the height information will be misleading in cases of visual uncertainty, such as when penetrating into an existing hole of the object. In such a situation having more that one modality allows the system to notice that while the visual information would suggest a penetration into the object, the force sensor will not observe contact and hence identify this case as a false success.

Furthermore, the force signal by itself is not sufficient for determining piercing. The changes in slope shown in Figure 2, even though closely related to the initial penetration into the target's surface, are strongly dependent on several other components, such as the velocity of the tool and the elastic properties of the material.

Figure 3 shows the increasing force profile (z-component) and the height of the tool, decreasing with penetration. Notice the variation in force, denotining surface penetration, around '400' on the time axis of force profile.

In this paper we have investigated the sensory signals registered during piercing operations. By using Discrete Event Theory, a formal model of a piercing operation has been developed. As a result, the proposed system is able to monitor in real-time the execution of the operation, and predicts possible consequences to actions. Future work will focus on the development of more detailed interactions between the motor control of the robot and the model, so as to allow real-time sensory-motor control of piercing. Furthermore, the study of signals obtained with different piercing tools will be considered in order to attempt the identification of the tool's properties with respect to the task and the context of application. Additionally, research will investigate the integration of machine learning capabilities.

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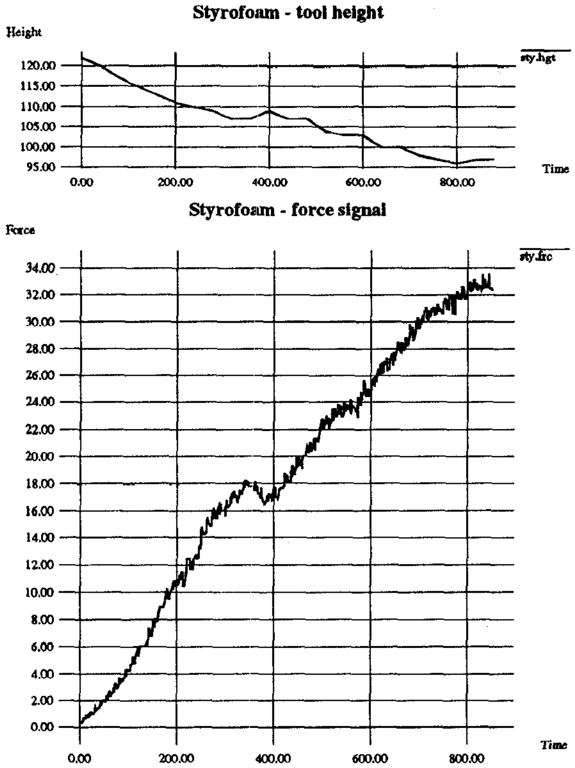
Styrofoam - tool height

Styrofoam - force signal

Figure 3: Height and force signals: units: time = 0.033 sec., distance = 1mm. velocity 1 mm./sec.