OBJECT EXPLORATION WITH A HUMANOID ROBOT
Using Tactile and Kinesthetic Feedback

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Abstract: This work deals with the reactive and autonomous exploration of objects with a humanoid robot using only tactile and kinesthetic sensor feedback. To coordinate the flow of the exploration, a novel hierarchical exploration system is introduced. The lowest level extracts contacts points and elementary features based on the direct contact with the object. It furthermore provides elementary movement primitives. The intermediate level consists of different controlling behaviors to generate exploration movements according to the sensor feedback. This level enables the robot to explore an object pointwisely or continously. The highest level evaluates the process of the exploration and determinates the reactive behavior of the underlying components. The evaluation scenario comprises the exploration of edges, which are arbitrarily located in space. The evaluation platform consists of a robot arm, a force-torque sensor, and a tactile sensor matrix. The proposed approach is evaluated and the different reactive behaviors as well as the used sensor modalities are compared.

1 INTRODUCTION

Service robots build a new block of research area. Their range of application highly differ from conventional industrial robot, as they are rather deployed in a domestic environment and are usually not intended for repetitive tasks with need for high precision or high forces. Typical tasks for a humanoid robot are all kinds of fetch and carry or manipulation tasks with a broad variety of objects. Not all of these object can be assumed to be known appriori. The robot might encounter unknown or partially unknown objects. Therefore, the robot has to use its sensors, like visual or haptic sensors, to explore an unknown object. The visual exploration is adequate to determine the location and the rough shape of an object but it is limited due to the ambiguity of visual data and the need for textured objects as well as good light conditions.

The haptic exploration describes the active palpation of objects. The relevant parts of the haptic exploration are the tactile perception (surface sensibility) and the kinesthetic perception (depth sensibility). A haptic exploration procedure of an object requires the direct interaction of the robot with the object. On the one hand, this delivers accurate 3D information about the object but, on the other hand, requires a reactive control strategy to bring the sensors into the right position.

Previous work in (Klatzky et al., 1987) (Lederman and Klatzky, 1987) identified the following exploration procedures from observing human exploration behavior: lateral motion, pressure, enclosure, and contour following.

These procedures allows to determine the texture, hardness, shape and size of an object by haptic exploration. The exploration procedure of this work primarily focuses on the procedure of contour following. Here, the tactile perception is represented by a tactile sensor matrix whereas the kinesthetic perception is given by a force-torque sensor. Robotic exploration procedures so far include approaches with grippers (Schmidt et al., 2006) and with tactile sensor matrices (Chen et al., 1995), (Heidemann and Schoepfer, 2004).

A major problem for such exploration tasks is the detection of a contact with the object to be explored. The limitation is usually given by the sensibility and the spatial resolution of the sensor. Therefore, many approaches using tactile sensors assume that the sensor is already located directly at the region of interest.

In order to avoid this restriction, this work introduces a novel approach by coupling the information of a force-torque sensor in the wrist and a tactile sen-

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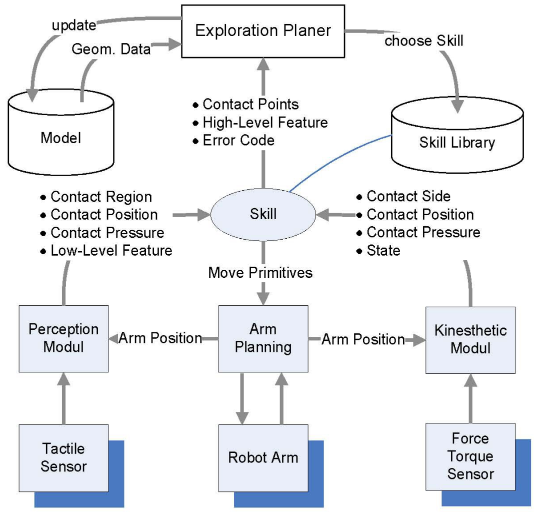


Figure 1: A system overview.

sor matrix representing the pose of an opened hand. This enables the robot on the one hand to detect direct contacts using the tactile sensor matrix, which are very accurate but less sensitive, and on the other hand to detect indirect contacts using the force-torque sensor and a model of the hand, which make it less accurate but very sensitive.

The remainder of this paper is structured as follows: After this introduction, the system overview of this approach is discussed in section 2 followed by the perception level in section 3. Our results are presented in section 4 before conclusions are given in section 5.

2 SYSTEM OVERVIEW

In order to consecutively determine the shape of an object, a concept consisiting of three components is introduced, as shown in figure 1. Here, the highest level is represented by the exploration planer. A reactive control layer complies with the skill library, from which consecutively a skill is chosen and executed. The haptic layer builds the lowest block of the framework and is realized by three components: tactile perception, arm planning and kinesthetic perception. The planning layer and the reactive control layer are explained in the following. The haptic layer is presented separately in section 3.

2.1 Exploration Planner

The exploration planner makes decisions based on the geometric shape of an object which can be determined by a successive palpation sequence. Based on the estimate of the object's shape, it determines the alignment of the robot towards the object. The planner executes a sequence of skills whereas the skills provides the planner with contact features during their execution. The planner evaluates the alignment towards the object and chooses a different skill if neccessary.

2.2 Exploration Skills

In this work, the exploration skills represent strategies to explore structures of an object. They are elementary operations for the exploration procedure and are executed by the superior global exploration component. A sequence of simple exploration skills leads to a complex exploration behavior.

Their key tasks are the coordination of the arm control and the creation of a defined exploration behaviors according to the preprocessed data. A skill has to fulfill two objectives. First of all, it has to bring the robot arm into the right position which is realized by a sequence of states. Secondly, it has to provide the planning level with an amount of contact points. To fulfill these tasks, a skill can access the underlying haptic components. The planning level supervises the execution of a skill and interprets the features provided by a skill in a global context.

A single skill is represented by a state machine which determines the flow of action. Such a skill is able e.g. to follow a structure or to rotate around a structure according to its task definition. The most states imply a coordination of sensor data and movements but also include instructions from the upper level. In general, the skills can be separated into two groups:

- Skills with discrete movements
- Skills with continuous movements

These two types of skills are explained in more detail in the following.

2.2.1 Skills with Discrete Movements

Skills with discrete movements are characterized by a palpation sequence as the skill departs from the object after establishing a contact before moving the arm to next position of interest. This is achieved by movement and control primitives which are the building blocks of the total movement. Movement primitives enable the robot to move with respect to a local or a global coordinate system. Control primitives also embed sensor data during a movement, e.g. to buildup a certain amount of pressure. Here, the communication between a skill and the planer is destinctive. The benefit is that structures can be explored systematically whereas the drawback is that they can only perform an alignment according to point contacts. They need

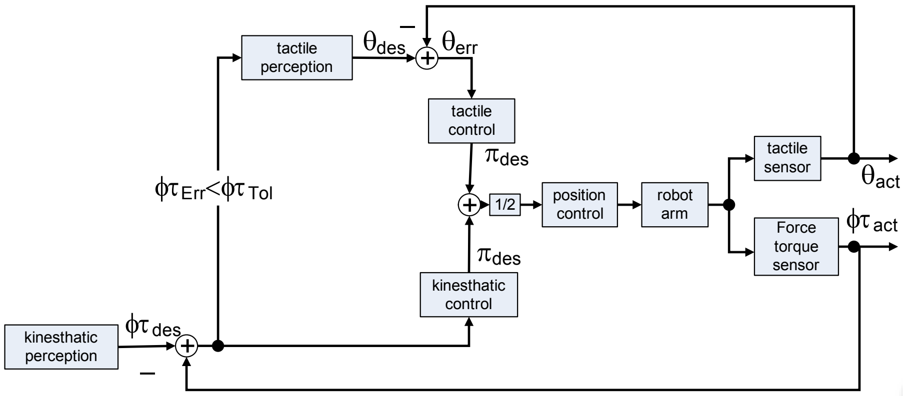


Figure 2: A control loop for skills with continous movements

at least two contact points to perform an alignment and also depend on the measuring accuracy of these contact points.

The process of tracking an edge, for example, can be summarized as a sequence of the control and movement primitives ¨move up¨, ¨move to the side¨, ¨move down", and ¨detect contact¨. A sequence of this skill results into a simple but effective exploration procedure.

2.2.2 Skills with Continuous Movements

The exploration behavior of skills with continuous movements is given by a complex control loop, e.g. zero-force control or a tactile control. At first, these kind of skills establish a contact with the object surface. Then, using a superior control loop, they try to keep a steady contact towards the surface. Figure 2 shows the basic structure of such a superior control loop. It shows a cascaded system with the force control preceding the tactile control. It is characterized by a coarse control based on the measured forces and torques of the force-torque-sensor and by a fine control based on the measured pressure profile.

The idea is to use the force-torque sensor to keep the applied pressure $\phi\tau_{des}$ stable. On the one hand, the applied pressure should not exceed a given limit as it could damage the robot or the object. On the other hand, the pressure should not be too little as the tactile sensor matrix would not be able to measure an adequate pressure profile anymore and the sensor pad could even loose contact to the object surface. The tactile control loop is activated as soon as the applied pressure is within an acceptable interval, expressed by $\phi\tau_{err} < \phi\tau_{tol}$. The tactile control loop is defined by the deviation θ_{err} of the center of the tactile image from center of the sensor pad. The position corrections τ_{des} are given to the position control of the robot. This enables the robot arm to align to the object and follow its surface.

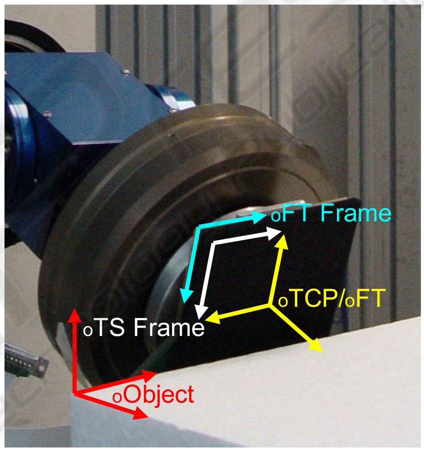


Figure 3: Setup of the evaluation platform and the involved coordinate systems.

3 PERCEPTION

The perception level is part of the lowest level. It preprocesses the data provided by the tactile sensor and the force-torque sensor. The perception in this work is therefore split into the tactile and kinesthetic perception. In the course of the paper, the tactile sensor matrix refers to the tactile perception whereas the force-torque sensor represents the kinesthetic perception. Figure 3 show the setup of the evaluation platform. It shows the tactile sensor and the force-torque sensor mounted to the robot arm. Furthermore, it illustrates the different coordinate systems which are involved in the perception layer.

The tactile sensor identifies very accurately the position of contacts caused by a direct touch. But a small change in the orientation of the tactile sensor matrix causes a significant chance in the resulting tactile image. Imagine an imprint of an edge on the tactile sensor, a small twist along the perpendicular image axis of the edge, makes the edge disappear until only a single point contact is determined. After a certain angle between the tactile sensor and the surface, no contacts can be detected as the sensor only turns normal forces into a pressure profile. This angle is called the **critical angle**.

The force-moment sensor, on the other hand, is not able to determine contacts in the inner regions of the sensor pad's surface. It can only detect the direction from the center point of the sensor to the border of the surface.

There is a simple decision rule for the determination of a contact, combining the tactile and the force-moment-sensor:

1. If the tactile sensor detects a contact, the contact must be inside the surface of the sensor pad. This is called a **TS-contact** and is the desired type of contact.
2. If the tactile sensor does not detect a contact but the kinesthetic perception does, the contact must be at the border of the sensor pad. We call this a **FTS-contact**.

It is obvious that the tactile sensor can only take a pressure profile if the robot apply enough force towards the direction of the object surface. Therefore, the more sensitive force-torque sensor is used to regulate the pressure applied to the object.

3.1 Tactile Perception

3.1.1 Working Principle

As already investigated and published by Weiss et al. (Weiss and Woern, 2005), the working principle of the tactile sensors depends on an interface effect between the metal electrodes and the structured conductive polymer covering the sensing electrodes. The resistance between the common electrode and a sensor cell electrode is a function of the applied load and time. This technique leads to very accurate pictures of the applied pressure profile and minimizes crosstalk between the sensor cells as well.

As each sensor cell represents a measured voltage, the voltage image has to be transferred to a pressure image. This characteristic curve of the tactile sensor can be obtained by calibration.

3.1.2 Tactile Feature Extraction

Identifying the characteristic features of an image using moments is a well known paradigm in image processing. The data of the tactile sensor matrix corresponds to a two-dimensional planar image. We analyze this image using moments up to the 2^{nd} order (Hu, 1962). The two-dimensional $(p+q)^{th}$ order moment $m_{p,q}$ of an image is defined as the following double sum over all image pixels (x,y) and their values $f(x,y)$:

$$m_{p,q} = \sum_x \sum_y x^p y^p f(x,y) \qquad p,q \geq 0 \ . \tag{1}$$

The moment $m_{0,0}$ constitutes the resulting force exerted on the sensor. The center of gravity $\underline{x}_c = (x_c, y_c)^T$ of this force can be computed to

$$x_c = \frac{m_{1,0}}{m_{0,0}} \tag{2}$$

$$y_c = \frac{m_{0,1}}{m_{0,0}} \ . \tag{3}$$

Using the center of gravity, we can verify that the object surface is aligned to the center of the sensor pad. It also allows to calculate the higher order moments with respect to the center of gravity, the so-called *central moments* $\mu_{p,q}$:

$$\mu_{p,q} = \sum_x \sum_y (x-x_c)^p (y-y_c)^q f(x,y) \quad p,q \geq 0 \ . \tag{4}$$

The 2^{nd} order central moments

$$\mu_{2,0} = \sum_x \sum_y (x-x_c)^2 f(x,y) \tag{5}$$

$$\mu_{0,2} = \sum_x \sum_y (y-y_c)^2 f(x,y) \tag{6}$$

$$\mu_{1,1} = \sum_x \sum_y (x-x_c)(y-y_c) f(x,y) \tag{7}$$

approximate the image by an ellipse and represent its principal axes. The eccentricity of a contact is described by the relation of the eigenvalues λ_1 and λ_2. If both eigenvalues have a similar value, then the contact area has a round shape and the eccentricity is close to zero. For these contacts it is not possible to calculate the orientation.

Touching an edge results in an oblong ellipse with an eccentricity ε close to 1 when using

$$\varepsilon = \frac{(\mu_{2,0} - \mu_{0,2})^2 + 4\mu_{1,1}^2}{(\mu_{2,0} + \mu_{0,2})^2} \qquad \varepsilon \in [0,1] \ . \tag{8}$$

A corner point results to an eccentricity close to zero. To control the orientation of the sensor pad with respect to the object surface, we are interested in the

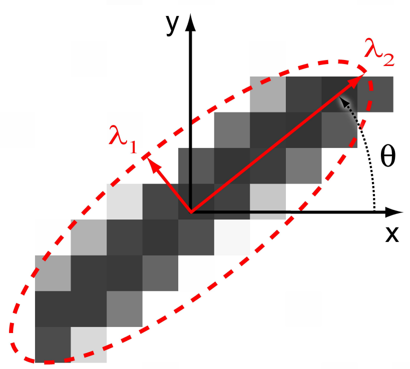


Figure 4: The angle θ between the principal axes of the tactile image and the sensor coordinate system.

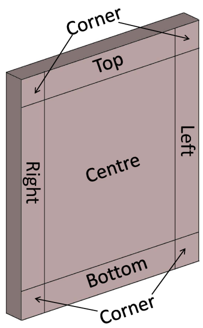


Figure 5: The 9 regions of the sensor pad.

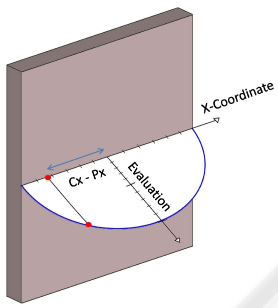


Figure 6: Evaluation of a contact point.

angle θ between the principal axes and the sensor coordinate system (cf. Fig. 4) which can be readily computed by

$$\theta = \frac{1}{2}\arctan\frac{2\mu_{1,1}}{\mu_{2,0}-\mu_{0,2}} \quad . \tag{9}$$

When tracking an edge, the desired angle θ is zero and can thus be directly used as the system deviation input to the controller to control one orientation DOF. The angle *theta* will be also referred to as the quality measure q_1 in the following.

To evaluate a contact point regarding to the orientation along the y-axis, we compute a quality measure from the distance $|y_c - y_p|$ of the contact point (x_c, y_c) to the center of the sensor pad called (x_p, y_p). As the correlation between this distance and the angle is not linear, we weight the distance by a circular function. This circular function f with the radius r is given by

$$f_r(x) = \sqrt{r^2 - x^2} \tag{10}$$

This results into the function

$$q_2 = \sqrt{y_p^2 - |y_c - y_p|^2} \tag{11}$$

Figure 6 illustrates the computation of this quality measure which is used for the alignment of the sensor pad towards the object surface.

Furthermore, we devide the pad into 9 regions: 4 corner regions, 4 border regions and one interior region, as shown in figure 5. Each region is checked, if it accommodates a contact or not. This computation results into a 9-dimensional binary feature vector which can be used for a simple classification like the determination of corner contacts or contact side, depending on the present context.

3.2 Kinesthetic Perception

The force-torque sensor that we use is an FTC 50-40 from SCHUNK. It has 6DOFs, with a range of $150N$ for the forces, $4Nm$ for the torques Mx and My, and $8Nm$ for Mz. The accuracy is 5%. The data is sampled every $1ms$ and transmitted via CAN bus with a baudrate of $500kbit/s$.

Since the data is quite noisy, the preproccesing of the sensor data includes a median filter with window size 7 to remove outliers. Since the tactile sensor pad is mounted on the top of the sensor, we must deduct its weight from the sensor values.

The compensation of the torques and forces is only possible in the global robot coordinate system and not in the local system. Local compensated forces are computed via back-transformation of global compensated forces into local coordinates. The required transformation steps are $f_l \rightarrow f_g \rightarrow f_{g,c} \rightarrow f_{l,c}$, where l and g mark local coordinated and global respectively. The marker c describes compensated values.

It is possible to determine contacts without the tactile sensor by relating the measured torques (m_x, m_y, m_z) with a model of the used sensorpad. The sensorpad can be described as a simple rectangle with the length (l_x, l_y). The angle α from the center of the pad to the contact point can be calculated by $atan(m_x/m_y)$. The angle furthermore describes, if a contact is safe or not. A corner contact is declared as unsafe, as is it not accurate enough to identify the correct contact side.

4 RESULTS

At first, the measuring accuracy of the contact points is investigated using the tactile and the force-torque sensor. Then, the implementation of a skill with discrete movements for edge tracking is shown. This skill is used to evaluate the exploration with each sensor in a stand-alone application and with a combination of both sensors. Finally, a skill with continuous movements is shown and evaluated.

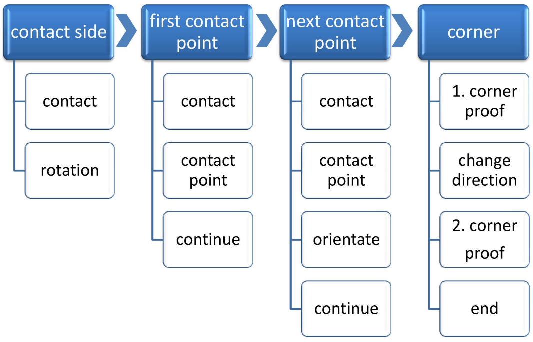


Figure 7: Implementation of a discrete skill.

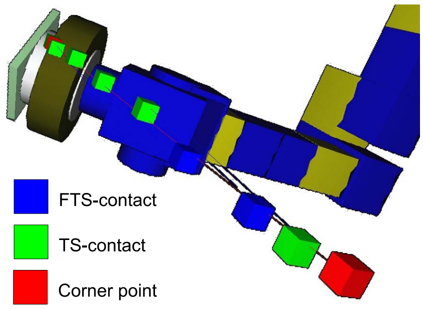
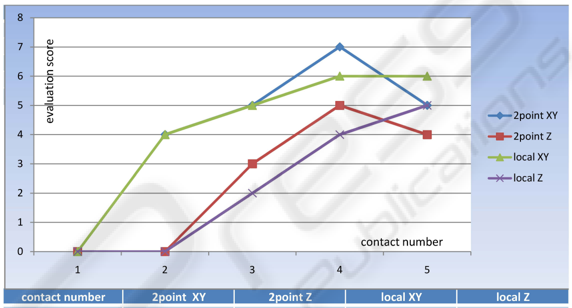


Figure 8: Visualisation of the exploration procedure.



contact number	2point XY	2point Z	local XY	local Z
1	0	0	0	0
2	4	0	4	0
3	5	3	5	2
4	7	5	6	4
5	5	4	6	5

Figure 9: Evaluation using only force-torque sensor.

4.1 Measuring Accuracy

To obtain the measuring accuracy of the tactile and the force-torque sensor, reference and measured points are generated consecutively along a line with a displacement of 1.0 cm in relation to the center of the tactile sensor pad. The measured contact points are determined by the interpolation of the contact area in the resulting tactile image. This simple experiment has shown that the used tactile sensor matrix with a cell distance of 0.6 cm has a mean square error of 0.2 cm. Furthermore, the accuracy is not correlated to the location of the contact point. A similar experiment has been done for testing the force-torque sensor. Here, the reference points were taken only at the boundary of the sensor pad. The measured mean square error is 0.6 cm.

The tactile sensor is superior to the force-torque sensor regarding the measuring accuracy. The tacile has one significant disadvantage - it exist a critical angle which restricts the operational area. Applying the maximum force of 8N towards a planar surface, the critical angle is 18 degrees. If the sensor pad is aligned with a larger angle towards the object, a contact cannot be detected anymore.

4.2 Discrete Skill for Edge Tracking

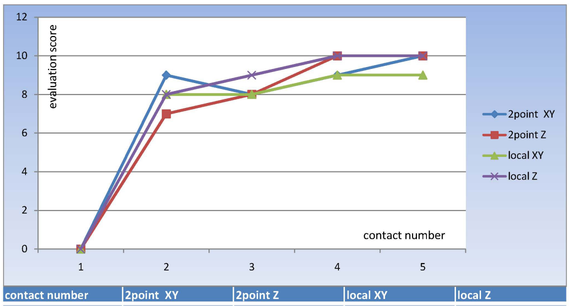
4.2.1 Implementation

The objective is a skill which pointwisely tracks an edge. Figure 7 shows a coarse view of the implementation of such a skill consisting of 4 main states and several sub-states. The skill tracks the contour of an edge and changes the direction of exploration as soon as the first corner has been detected. The first state involves the determination of the first contact and the contact side. Therefore, the robot arm moves into a specified direction until it detects a contact and departs again. According to this first contact, the orientation of the sensor pad is aligned so that the long side of the pad is used for tracking the edge. After this initial alignment, the first contact point is collected and the arm departs again. The first two steps are only executed once.

The third step is executed consecutively until a corner point and hence the end of the edge is detected. This step collects the next contact point, departs from the object, evaluates the current spatial alignment, and executes a correction of the alignment. If a corner is detected by the tactile perception, the fourth phase is triggered which involves the decision to change the direction of the exploration, if the first corner has been detected, or to stop the exploration if the final corner has been found. Figure 8 visualizes the outcome of such an exploration procedure: a set of points and lines.

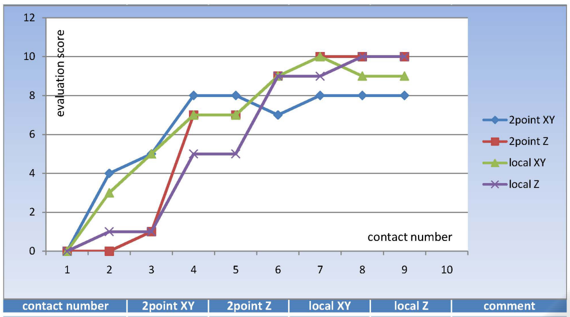
4.2.2 Force-torque Sensor vs. Tactile Sensor

To compare both sensors, the implemented skill has been executed once only with the force-torque sensor and another time only with the tactile sensor matrix. In order to make the skill be executable for both sensors in a stand-alone application, several requirements must be considered. At first, the sensor pad was aligned with an angle of 10 degrees towards the object. Secondly, the exploration procedure only in-



contact number	2point XY	2point Z	local XY	local Z
1	0	0	0	0
2	9	7	8	8
3	8	8	8	9
4	9	10	9	10
5	10	10	9	10

Figure 10: Evaluation using only tactile sensor.



contact number	2point XY	2point Z	local XY	local Z	comment
1	0	0	0	0	FT-contact
2	4	0	3	1	FT-contact
3	5	1	5	1	TS-contact
4	8	7	7	5	TS-contact
5	8	7	7	5	edge
6	7	9	9	9	TS-contact
7	8	10	10	9	TS-contact
8	8	10	9	10	TS-contact
9	8	10	9	10	edge

Figure 11: Evaluation using force-torque sensor and tactile sensor.

volves tracking the edge in one direction up to the first corner, as the force-torque is not able to detect the corner of an edge. After the second contact point, the alignment towards the edge is evaluated.

For tracking an edge two alignments are needed. At first, the imprint of the edge must be parallel to a specified boundary of the sensor pad. Secondly, the center of gravity of the contact point must be in the center of the sensor pad. For these two alignments, two quality measures were introduced in section 3. For the sake of convenience, these two quality measures will be scaled to a score from zero to ten whereas ten indicates a good score. The score *XY* refers to the difference between the center of the contact point and the center of the sensor pad, as described in equation 11. The second score *Z* refers to the deviation of the angle of the edge, as stated in equation 9. The prefix *2-Point* indicates that only the last two contact points are used for an estimate of the edge whereas the prefix *Local* points out that all extracted point so far are taken into account.

Both experiments haven been repeated several times. Representative results of both experiments are shown in figures 9 and 10. The diagrams plot four curves which result from two quality measures for the current alignment, labelled *2-Point-XY* and *2-Point-Z* and two quality measures for the alignment over several exploration steps, labelled *Local-XY* and *Local-Z*.

As to be expected, the tactile sensor scores well with an average score of about 9 points for both quality measures. The results of the force-torque sensor is worse with an average score of 5 points. Furthermore, the tactile edge tracking converges faster towards the optimum of the quality measures. Both sensors enable the robot to explore an edge considering some restrictions but both sensors also complement each other. The FTS-determination of contacts points is less accurate but independent from the edge angle. It allows the alignment of the sensor pad so that the critical angle of 18 degrees is under-run and the tactile sensor can take over the exploration procedure in order to undertake a more precise computation of the edge.

4.2.3 Combination of Both Sensor

Finally, the edge tracking with a combination of both sensor is evaluated. The initial angle is 25 degrees which exceeds the critical angle. Figure 11 shows the result of the exploration procedure. The additional comment shows one of the three possible states of the contact point: FTS-contact, TS-contact, and corner point. As predicted, the orientation of the edge can be calculated only by the use of the force-torque sensor so that the tactile sensor can take over the exploration after two FTS-contacts. Significant is the increase of the quality measures after the tactile sensor has taken over. After this, the tactile sensor does not loose control over the exploration procedure at any time.

4.3 Continous Skill for Edge Tracking

The next experiment involves a skill with continuous movement according to the proposed control loop presented in section 2. The task is to follow the edge without loosing contact to the object surface. For this kind of skill only the accomplishment of certain phases is checked. This experiment has been performed five times.

The first phase involves the alignment of the pad towards the edge using zero-force control followed by the tracking of the edge until the first corner point. The third phase involves the return to the starting position and tracking towards the opposite direction. In all experiments, all phases were completely accomplished. Significant is that this exploration procedure took one third of the time compared to the edge tracking skill based on discrete movements (250s vs. 80s).

4.4 Comparision of Both Skills

The skill with discrete movements as well as the skill with continous movements are capable to completely explore an edge. Both skills have benefits and disadvantages. The benefit of the skill with continuous movements is its speed and its simplicity as it needs less states compared to the other skill. In particular, the fast alignment towards the edge using an adapted zero-force control has to be pointed out. As the skill with discrete movements has at first to collect single points to perform the alignment gradually, the skill needs more time and more control processes. Otherwise it is easier for a superior level to supervise these discrete movements. As outliers can be detected by collecting a great amounts of contact points, the exploration behavior becomes very stable. For the exploration of unknown structures, collecting single points is still favored, as it provides the superior level with more possibilitys for interaction. Skills only based on a control algorithms need the whole flow of information for the spatial alignment and are not made for interaction. A combination of both approaches seems to be promising.

5 CONCLUSIONS AND FUTURE WORKS

This work introduced a novel framework for the exploration of objects using haptic feedback. This framework consists of three layer: an exploration planner, a skill library with reactive exploration behaviors and a haptic perception layer. Two different skill schemes have been introduced: skills with discrete and skills with continuous movements. The performance of our approach has been evaluated in the evaluation scenario of tracking an edge which is arbitrarily located in space. The tactile sensor and the force-torque complement one another. The determination of contact points using a force-torque sensor is less accurate but independent from the edge angle. It allows the alignment of the sensor pad so that the critical angle for the tactile sensor is under-run and the tactile sensor can take over the exploration procedure in order to undertake a more precise exploration procedure.

Furthermore it became apparent that the exploration with discrete and the exploration with continuous movements have both benefits and drawbacks. The continuous exploration based on a control behavior is faster but provides less possibilities for interaction. Exploration procedures with discrete movements are slower but are more robust and better to supervize. A combination of both approaches seems to be promising. Future work will include the extension of the skill library and the transfer of an exploration behavior on a humanoid robot hand.

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