Telepresence Techniques for Exception Handling in Household Robots*

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Abstract – *The hardware for humanoid household robots will be available in the near future. As households are unstructured domains and interaction with human users is ambiguous, these robots encounter unexpected situations, so called exceptions. These render the robot unusable, if not handled fast and transparently to the user. Telepresent exception handling gives the technical staff an intuitive interface to the robots and is transparent to the client. We propose a service center for telepresent exception handling, which is directly available and thus allows the use of humanoid domestic robots as soon as the corresponding hardware is commercially available.*

1 Introduction

In the near future, humanoid household robots will be available at reasonable costs. These robots are designed to help human users in their everyday work. That means, they will not only perform autonomous or semi-autonomous tasks but will have to directly interact with their human users. The interaction with human users is typically ambiguous and thus prone to errors.

In addition, the household domain is especially unstructured and variable, which makes it hard for the robot's control software to provide solutions for all possible situations. This leads to the fact, that robots encounter exceptions, i. e., situations where planning or execution fails. In order to keep the robot always working, these exceptions have to be handled, automatically or by service staff, the so called operators. To establish humanoid household robots in the period of the next few years, it is important that these exceptions are handled fast and invisibly to the user. Even if those exceptions only occur rarely, unhandled exceptions render the robot virtually useless, as it is blocked until the exception is handled.

Only a small number of exceptions in household robots can be handled automatically. These exceptions include such problems as blocked passages [5] or problems in simple tasks, like gripping objects [13].

In this paper we propose a service center for telepresent exception handling, which allows to handle exceptions transparently to the user, cost effectively, and fast.

In order to handle those exceptions, that cannot be handled automatically, an operator teleoperates the robot. Interfaces for robot telecontrol typically use joysticks [11] or PDA-based remote controls [4]. These interfaces, though easy to use for steering a robot, hardly allow to control a humanoid robot with all its degrees of freedom.

Immersive telepresence interfaces allow the operator to concentrate on the given task. He then perceives the target environment through a head mounted display. Omnidirectional treadmills [2, 6] allow him to move freely and naturally in the target environment. Those devices, however, are expensive and hold a high risk of injury.

The remainder of this paper is structured as follows. In Section 2 we will discuss the various types of exceptions, that can occur in household robots and define the requirements for the handling of these exceptions. Section 3 describes the service center for exception handling, that satisfies the requirements given. In Section 4 we discuss future enhancements to the current methods and finally Section 5 describes the prototypical service center set up at our laboratory.

2 Problem Formulation

2.1 Exceptions

Exceptions in household robots can arise from various reasons. An obvious reason for an exception is a hardware failure, e. g. a stuck joint. These exceptions can be recognized by automatic diagnosis tools. The robot then has the possibility to use alternative control schemes until the hardware is repaired. For hardware repair, however, presence of service staff is needed. These exceptions only occur rarely.

A much more frequent reason for exceptions is a result of the robot's interaction with its environment. Often, planning or execution of new tasks does not terminate correctly due to erroneous interaction with human users. In execution this means for example unexpected changes in the environment. The user might have moved an object the robot is trying to pick up, or the robot did not recognize an object correctly. Exceptions in planning usually occur, when the robot is not able to find a plan for a given task, e. g. when the task itself is unknown, or the robot does not know how to handle certain objects.

New robots delivered from the factory will typically not be fully trained for their future application, but will come equipped with only a set of basic skills. These skills will have to be adapted by an operator in the initial training phase. This adaption includes for example learning the layout of the application environment. As the intervention of an operator is needed during the initial training phase, we also classify it as an exception.

All those exceptions, where human intervention is needed, but actual physical presence of the operator is not required, can be handled remotely by teleoperation.

2.2 Requirements

Successful handling of the exceptions stated above is essential for the general acceptance and usability of robotic systems in households. The different parties involved in operating the robots, of course, have different requirements for exception handling. These parties are the users, the operators, and the service providers.

We will now discuss the main requirements of the parties involved to exception handling.

2.2.1 Transparency

Users do not want to be bothered with their robot issues. They want an always fully working system out of the box. The presence of an operator in their homes is usually not desired and should be kept to a minimum.

2.2.2 Intuitive Interface

Operators need an intuitive interface for exception handling, that can be used with only little training. This allows the operators to focus on the given task and not on handling the robot. This is especially important as the application environment is usually unknown to the operators and thus needs a lot of attention.

2.2.3 Scalability

To keep the costs of service low, the service providers require the system to scale well with the number of robots supervised. That means the costs for supervising robots should rise slower than the number of robots. In order to achieve this, one operator should be to supervise multiple robots. To further lower the costs, multiple operators should be able to share one working place.

3 A Service Center for Robot Teleoperation

In order to satisfy the requirements above, we propose the idea of a service center for household robots. By means of this service center operators can supervise and teleoperate multiple robots. If, for example, the user commands his robot to go to the kitchen and fetch a teapot, but the robot does not know what a teapot looks like and how to handle it, it runs into an exception. The operator is informed about this exception and can now switch to the robot and teleoperate it. This is absolutely transparent to the user, who only perceives his robot fetching the teapot. As soon as the exception is handled, the operator switches control back to the robot, that continues working autonomously. Although, the robot is only teleoperated for a short time compared to the autonomous phase, using a robot in a household today will not be practical without teleoperated exception handling, as exceptions might lead to long down-times of the robot.

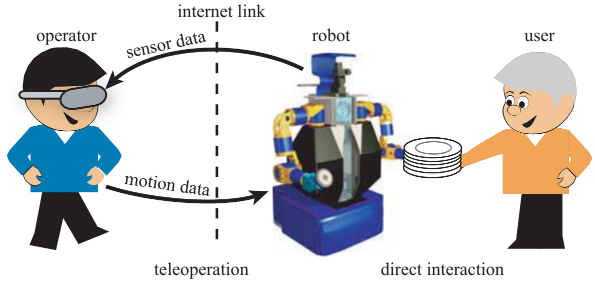

Figure 1: Operator teleoperating a robot during an exception. The user perceives his robot working normally.

In order to give the operator an intuitive interface to the robot, we implemented a telepresence interface, which allows the operator to benefit from his natural navigational skills [10]. This is especially important when switching between different target environments.

For that purpose, the operator's hand and head motion is tracked by a tracking system and transferred to the robot. The robot imitates this motion and thus affects the target environment. The robot, in turn, gathers sensory information which is transferred and presented to the operator. This information includes stereo vision, which the operator perceives through a head mounted display, stereophonic audio via headphones, and haptic feedback.

The operator can move freely in the service center, but perceives the robot's environment, the target environment. As the effects of his actions take place in the target environment, he has the sensation of actually being present there. As a result, he identifies with the robot and controls it from within. This state is called telepresence. In our example this means, that the operator can naturally walk to the kitchen and fetch the teapot as if he were actually present in the target environment. He almost does not perceive that he is teleoperating a robot. Thus the service center is an intuitive interface for robot teleoperation, which does not need highly trained operators.

In order to achieve the desired scalability, one operator supervises several robots and only teleoperates them when needed. To keep the number of operator interventions low, the robot should learn new tasks and adapt its skill during teleoperation, i. e., the robot learns from the operator's demonstration how a teapot looks like and how to grip it. If several operators share one service center, the system scales even better. This case is referred to as multi-operator service center.

In a system like the one described above, the target environment is limited to the size of the service center or the range of the tracking system. It is, however, desired to teleoperate a robot in an arbitrarily large target environment from a relatively small service center. This can be achieved through scaling [7] or walking-in-place like metaphors [12], but those methods lead to a substantial loss of immersion, i. e., the feeling of presence. Motion Compression [10] achieves the desired effect, which is important to keep the interface as intuitive as possible. We will now give a short introduction to Motion Compression as it is a substantial part of the service center.

3.1 Motion Compression

The Motion Compression algorithm consists of three functional modules.

3.1.1 Path Prediction

In the path prediction module the operator's desired path in the target environment is predicted. This path is called the target path.

3.1.2 Path Transformation

Path transformation finds a nonlinear transformation of the target path, in such a way, that the resulting transformed path fits into the service center. This path features the same length and the same turning angles as the target path. The two paths, however, differ in path curvature. The transformed path is optimal with respect to the difference of path curvature. This is important, because the operator does not perceive small deviations between the visual feedback and his proprioception, i. e., sense of self-motion, but large deviations lead to a substantial loss of immersion.

3.1.3 Guidance

In the guidance module, the operator is guided onto the transformed path exploiting his navigational capabilities. We will explain this by means of an example.

In our example, the target path is predicted as a straight line as depicted in Fig. 2(a). The path transformation module transforms the target path into a path curved to the left in the service center. The operator is now to be guided on this transformed path.

As the operator is wearing a head mounted display and is presented the visual perception of the robot, i. e., he sees through the robot's eyes, operator and robot are coincident. As the operator moves a short distance straight ahead in the direction where he saw the target, he leaves the transformed path, resulting in the robot leaving the target path. The robot's new position and orientation in the target environment reflects a motion curved to the right. The operator now sees the goal to his left as shown in Fig. 2(b). He compensates for the deviation by turning toward the goal and thus moves along the transformed path (Fig. 2(c)).

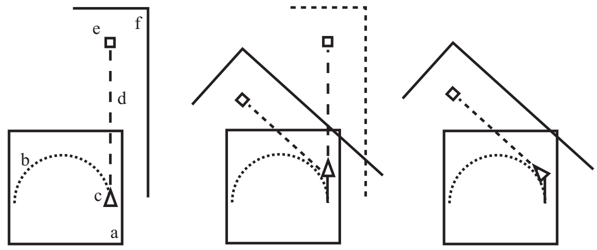

Figure 2: Guidance in Motion Compression.

4 Further steps toward the Service Center

With the existing methods we can set up a service center with one operator supervising multiple robots. The head and hands of the operator are tracked and his motion is transferred to simulated robots, that follow his actions with only very little delay. Through use of Motion Compression the operator can teleoperate a robot in a target environment much larger than the service center. To obtain service center with all the features described above, additional functionalities and improvements to Motion Compression are needed.

In order to improve the scalability of the system, the robots should need less operator attention by the time. This can only be achieved if the robots learn new skills and behavioral patterns during teleoperation. We plan to integrate the techniques of programming by demonstration [3] into the service center. The operator's motion during exception handling are recorded and used as training examples for the robots. For better results, the actions can be commented during or after teleoperation.

For a real intuitive teleoperation of the robot, the operator needs haptic feedback from the target environment. A haptic interface for a service center using large scale telepresence has special requirements. The interface needs to be available throughout the service center and must not interfere with the operator's motion. In [9] a prototype for a mobile haptic interface is presented, which moves along with the operator.

4.1 Importance of Prediction

Prediction is an important problem in telepresence. Telepresent operation of a robot is heavily affected by delays arising for example from tracking the operator or transferring the camera images through the network. In order to compensate for these delays, a good short-term prediction of the operator's motion, like looking around or accelerating, is needed. The robot can then be controlled predictively, i. e., the robot's motion is ahead of the operator's.

When using Motion Compression, we also need long-term prediction of the operator's motion. This includes for example his decision to move toward a specific goal and the path to the goal he plans to use. This kind of prediction is necessary for path transformation. The better goal and path are predicted, the lower is the curvature difference between the target path and the operator path. This is especially important when teleoperating a robot in narrow apartments, as the operator is likely to make lots sudden direction changes due to passages blocked by furniture or people.

4.2 Improvements to Motion Compression

As described above, prediction is one of the most crucial problems in telepresence applications. This is why optimization of Motion Compression is mainly related to optimization of operator prediction.

4.2.1 Goal Prediction

For a better long-term prediction we plan to use a combined psychological and stochastic model as shown in Fig. 3.

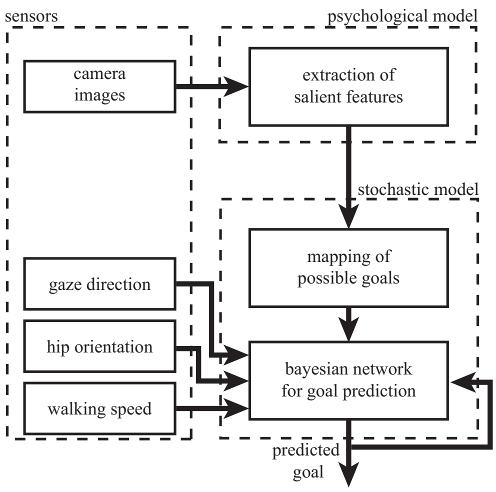

Figure 3: Combined psychological and stochastic goal prediction.

It is assumed that a human operator always moves toward salient features [1] in the target environment. These are for example colorful objects, or objects with a texture significantly different from their environment. The latter case is for example a white plate on a wooden kitchen table or a broken jar on the floor.

The images from the cameras on the robot are used to build saliency maps, which combine features extracted from histograms, intensity and texture. From these maps the most salient features are chosen to be interesting points in the environment. The robot calculates the positions of the salient features by stereo reconstruction and adds them as possible goals to a map of the target environment.

The actual goal of the operator is now to be selected based on the stochastic model. The simplest solution is choosing the goal based on gaze direction. The longer the operator looks in the direction of one possible goal the more likely it is the operator's actual goal. Besides the gaze direction we plan to incorporate information from other sensors into the prediction, e. g. the orientation of the operator's hip and acceleration and deceleration of his motion. Deceleration for example is a good hint, that the operator is likely to change his direction, while he will only accelerate if he is going to move straight forward. To prevent switching back and forth between a number of possible goals, a feedback of the current predicted goal is used as additional virtual sensor. In order to combine the data from the various sources we plan to use a new type of hybrid bayesian network, which is currently under development at our laboratory.

4.2.2 Mapping of Spatial Properties

If the operator turns toward the edge of the service center, the resulting transformed path will be highly curved. The algorithms behavior in this case can be improved if the spatial properties of the target environment are taken into account.

If the operator is moving into a corner of the target environment, the possibilities for future moving directions are limited to the two open sides. This leads to the conclusion,

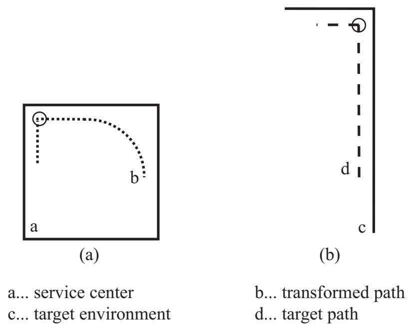

Figure 4: Influence of mapping corners.

that mapping corners and walls of the target environment onto corners and edges of the service center can reduce the curvature deviation between those paths, as close to the corner both paths have identical curvature and the service center's available space is used much better. Figure 4 compares the operator's path in the service center (a) and the robot's path in the target environment (b) if the corner is mapped.

4.2.3 Feedback Controlled Guidance

During teleoperation with standard Motion Compression, operators and as a result the robots tend to leave the predicted and transformed path. Thus the algorithm has to calculate a new path transformation at every time step. The new transformed path is not necessarily consistent with the old operator path, which makes the robot's and the operator's movements hard to predict, and thus does not allow predictive control. Better predictability can be achieved by adding a closed loop controller to the guidance module. This controller keeps the operator on the desired path and thus makes the path more predictable allowing predictive control of the robot.

4.2.4 Arbitrarily Shaped Service Centers

There are further necessary improvements to the Motion Compression algorithm. At the moment, the service center is limited to convex shape. In order to make better use of the available space and to keep the difference in curvature low, the path transformation will be modified in order to allow for arbitrary shaped service centers. This is especially important if multiple operators share one service center, since their paths have to be transformed simultaneously and the available free space for each operator will typically not be of convex shape.

5 Prototypical Setup

A first prototype of the service center has already been set up (Fig. 5). The operator's head and one of his hands are tracked by an acoustic tracking system developed at our laboratory.

Head and hand motion are compressed by Motion Compression and transferred to a virtual target environment modeled with MAVERIK [8]. At the moment the only sensory feedback to the operator, is vision. The view of the virtual target environment is presented through a high-resolution head-mounted display for better immersion. Additional information about exceptions is augmented into the operator's display.

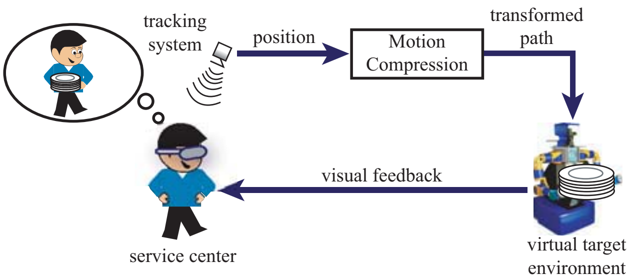

Figure 5: Schematic overview of the prototypical setup of the service center.

The operator can switch between multiple virtual household robots and solve a simple problem. Figure 6 shows an operator in the service center teleoperating a robot. Figure 7 shows the corresponding image displayed to the operator.

The current setup only has very basic path prediction. It is assumed that the operator's goal is situated 35 m in gaze direction. Although, this works fine in large rooms, it leads to highly curved paths in narrow apartments. As only the direction toward the goal is known but not its position, the transformed path will guide the operator close to the edge of the service center. This is shown in Fig. 8(a). When the operator reaches his goal, he might decide to turn toward the edge of the service center and move ahead. In order to fit into the service center, the transformed path has a high curvature while the predicted path does not. Through the effect of the guidance module, this gives the operator the impression of

Figure 6: An operator with head-mounted display, head tracker and hand tracker.

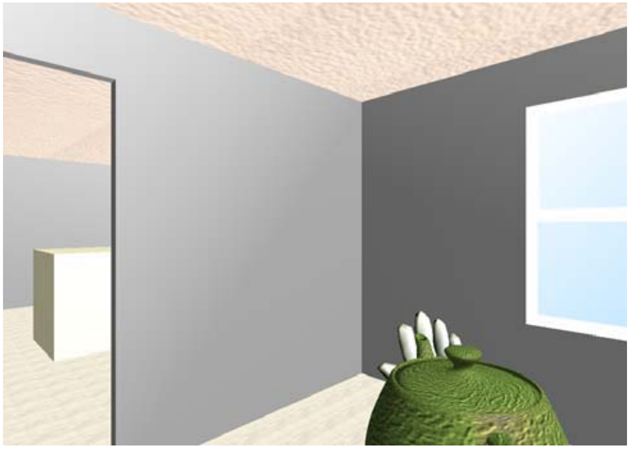

Figure 7: Telepresent carrying of a teapot in a virtual scenario.

the target environment turning around him and thus leads to loss of immersion.

After integration of the proposed mechanism for path prediction, the intermediate goal of the operator will be known. The algorithm can then transform the path in a way, that it ends close to the center of the service center. As shown in Fig. 8(b), the operator will then be able to turn in any direction without causing high path curvature. This leads to better immersion although the overall path curvature might be higher than in the first example.

We already included a first improvement of the Motion Compression algorithm into the service center. This modification is the closed control loop in guidance as described above. When the operator leaves the transformed path, his perception of the target environment is modified in such a way that he moves back on the path. An intuitive description of this modification would be that the robot turns his head away from the goal. The operator then perceives his goal further off, than it actually is and turns further toward it. More details will be presented elsewhere.

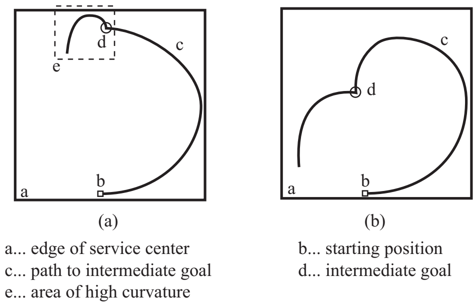

Figure 8: Example for an operator turning toward the edge of the service center.

During a demonstration of the system several untrained people teleoperated the virtual robots. Almost all of them managed to navigate through a virtual environment and were able to switch to an exception. They could handle this exception by performing a simple task, which was fetching a teapot from another room of an apartment. It was observed, that especially younger operators adapted fast to telepresence.

6 Conclusions

In order to establish robots as useful helpers in households, it is important that they are always fully working. However, as a result of unstructured environments and interaction with human users, they run into unexpected situations, so called exceptions. In order to handle these exceptions transparently to the user and with low costs for the service providers, we presented the idea of a service center for robot teleoperation. This service center provides the operators with an intuitive interface to the robot, namely telepresence. We discussed possible enhancements of the Motion Compression for large scale telepresence.

Our prototypical setup shows the practicability of the service center for exception handling in household robots. The proposed service center is, however, not only limited to the application given, but it also qualifies as intuitive user interface to virtual reality and other software, and can thus be used in working, training, recreational, and gaming scenarios.

Acknowledgments

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