A NOVEL HAPTIC INTERFACE FOR FREE LOCOMOTION IN EXTENDED RANGE TELEPRESENCE SCENARIOS

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Abstract: Telepresence gives a user the impression of actually being present in a distant environment. A mobile teleoperator acts as a proxy in this target environment, replicates the user's motion, and records sensory information, which is transferred to the user and displayed in real-time. As a result the user is immersed in the target environment. The user can then control the teleoperator by walking naturally. Motion Compression, a nonlinear mapping between the user's and the robot's motion, allows exploration of large target environments even from small user environments.

For manipulation tasks haptic feedback is important. However, current haptic displays do not allow wide-area motion. In this work we present our design of a novel haptic display for simultaneous wide area motion and haptic interaction.

1 INTRODUCTION

Telepresence aims at giving a human user the impression of actually being present in a remote environment, the *target environment*. In order to achieve this, a robot, the *teleoperator*, typically a wheel based platform equipped with a camera head, is placed in the target environment. Optionally, the teleoperator may be equipped with a manipulator arm.

In order to control the robot, the user's head motion is tracked and transferred to the teleoperator that replicates this motion. The teleoperator records sensory information and sends it to the human user in real time. This information is displayed to the user on immersive displays, e. g. a head-mounted display for video and headphones for audio, in such a way that the user only perceives the target environment. As a result, the user is immersed in the target environment, i. e., he feels present.

The more of the user's senses are telepresent the deeper he gets immersed in the target environment. Fig. 1 shows the senses most important for telepresence. Since proprioception, the sense of self motion, is especially important for human navigation and wayfinding (Bakker et al., 1998), extended range telepresence allows the user to navigate the teleoperator by natural walking, rather than using devices like joysticks (Stemmer et al., 2004) or steering wheels (Bunz et al., 2004).

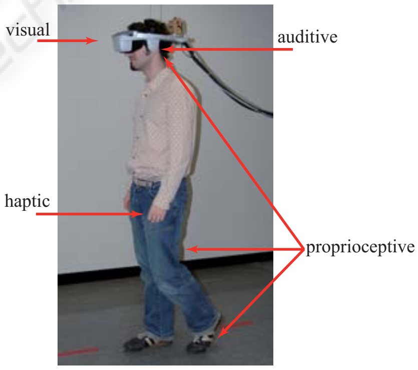

Figure 1: Senses of interest in telepresence. The photo shows the setup used in (Rößler et al., 2005b).

The target environment may be of arbitrary size, but the user's real environment, the *user environment*, is typically limited, for example by the range of the tracking system or the available space. In order to allow the user to explore target environments that are larger than the user environment, additional processing of his motion data is needed. Motion Compression (Nitzsche et al., 2004) provides a nonlinear map-

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ping between the path in the user environment and the path in the target environment. It guarantees a high degree of immersion by providing almost consistent proprioceptive and visual feedback.

A system such as the one described above allows telepresent exploration of large target environments (Rößler et al., 2005b). However, in order to be able to perform manipulation tasks in the target environment, haptic feedback is needed.

Haptic feedback can be achieved by implementing a robotic system, that applies forces on the human user, e. g. his hand. Most current haptic interfaces like the commercially available Phantom (SensAble Technologies, 1996) use classic serial kinematics. Even industrial robots are sometimes used as haptic interfaces (Hoogen and Schmidt, 2001).

Besides these classical approaches there is also a group of interfaces based on completely different principals, like for example magnetic levitation (Unger et al., 2004). Common to all such systems is a very limited work space. Therefore, they are not suited for extended range telepresence, where the user needs to move freely in the user environment.

One approach to solving the problem of simultaneous haptic interaction and wide are motion are ungrounded haptic displays, e. g. exoskeletons (Bergamasco et al., 1994), which are carried along by the user. However, with these devices haptic rendering is of significantly lower quality than with grounded displays (Richard and Cutkosky, 1997).

As various applications need large haptic interfaces, there are a number of different approaches fitted for each application. Some of these displays however, only extend the height of the work space (Borro et al., 2004). Some translatory motion in the user environment is allowed by a system based on a wire pull mechanism (Bouguila et al., 2000). However, rotational motion is highly restricted as the user gets caught in the wires. Hyper-redundant serial kinematics (Ueberle et al., 2003) feature a large work space that allows translatory and rotational motion, but still restrict free motion in the user environment.

The only group of systems that allows haptic interaction during wide area motion are mobile haptic interfaces (Nitzsche and Schmidt, 2004). These are typically small conventional haptic devices mounted on mobile platforms. However, they are hard to control and display quality is heavily dependent on localization of the mobile platform.

In this paper we present our patent pending design of a large haptic interface that allows simultaneous haptic interaction and wide area motion. The design of the system provides a high degree of stiffness and makes it fairly easy to control. Although especially designed for use in systems with Motion Compression, it is more general and opens a wide variety of applications besides robot teleoperation, for example in virtual reality or entertainment (Rößler et al., 2005a).

The remainder of this paper is structured as follows. In Sec. 2 we review Motion Compression, as this algorithm heavily affects the requirements to the haptic display described in Sec. 3. The mechanical setup of the display is given in Sec. 4 along with its kinematic properties. Sec. 5 describes the distributed electronic control system, which was developed to control this large robotic system with many sensor/actuator subsystems. The safety architecture necessary for safe operation of such a system is presented in Sec. 6. Finally, Sec. 7 draws conclusions and discusses future work.

2 MOTION COMPRESSION

Motion Compression is an algorithmic framework that provides a nonlinear transformation between the user's path in the user environment and the mobile teleoperator's path in the target environment. It consists of three modules as shown in Fig. 2.

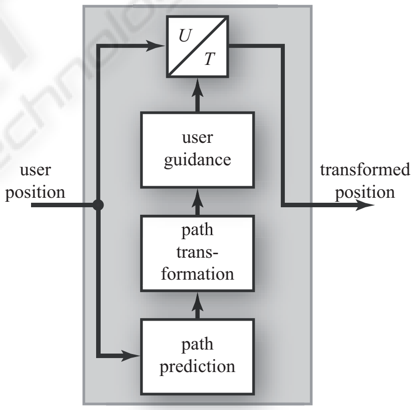


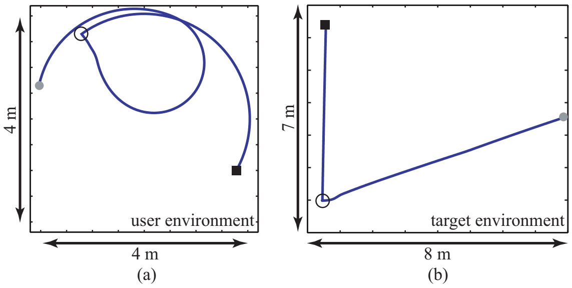
Figure 2: Overview of the Motion Compression Framework.

Path prediction tries to predict the desired path of the user in the target environment. This prediction is based on tracking data and, if available, information on the target environment. The resulting path is called *target path*.

In the next step, *path transformation*, the target path is transformed in such a way that it fits in the user environment. The transformed path features the same length and turning angles, while path curvature differs. The resulting *user path* minimizes this path curvature difference. A target path and a corresponding user path are shown in Fig. 3.

Finally, the *user guidance* module guides the user on the transformed path, while he has the impression of walking on the original path. User guidance exploits some properties of natural human wayfinding.

The result of these three modules is a linear transformation between the user's position in the user environment and the teleoperator's position in the target environment at any position and time. This transformation can also be used to transform the user's hand position, or to transform force vectors recorded by the teleoperator back into the user environment.



(a) (b)

Figure 3: The corresponding paths in both environments. (a) User Path in the user environment. (b) Target path in the target environment.

3 REQUIREMENTS

As a result of using Motion Compression, there arise requirements for the kinematics of the haptic display. In order to control the robot by natural walking, the user needs a work space that covers the whole user environment of $4 \times 4\,\mathrm{m}^2$, in which he may move with a natural speed of up to $2\,\mathrm{m/s}$. Especially the rotational motion around the vertical axis must be *unconstrained* and *indefinite*. To give the user the possibility of manipulation, the work space should have a height of at least $2\,\mathrm{m}$.

As this work does focus on haptic sensation during wide motion and not on precise haptic manipulation, only forces have to be displayed, the moments are of lesser importance. Thus the end-effector of the display needs four degrees of freedom, three translatory and one rotational around the vertical axis.

A robotic system of the size described above features long distances between the sensor/actuator units. Thus a distributed electronic control system is needed that allows, for example, decentralized pre-processing of sensor data. These decentralized units have to be connected to a central control unit by means of a bus system that allows high bandwidth and a high number of sensor/actuator subsystems.

As the user will be in direct contact with a robotic system moving at high speeds, a safety architecture that reduces the danger of physical harm to a minimum is needed. This is even more important, as the user is immersed in the remote environment and does not see the haptic display itself. In case of malfunction of any part of the system, all subsystems, especially all moving parts, immediately have to stop.

4 MECHANICAL SETUP

Fine haptic rendering and wide area motion require very different characteristics regarding mechanics as well as control. This is why we decided to follow the idea of mobile haptic interfaces and separate the haptic display device from wide area motion. The motion subsystem is realized as portal carrier system with three linear degrees of freedom, that moves the haptic end-effector along with the user. The haptic end-effector is realized as a parallel SCARA manipulator. Fig. 4 gives an impression of the complete setup.

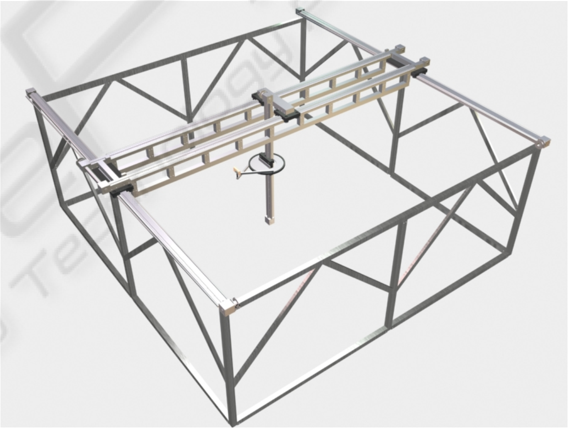


Figure 4: An impression of the complete setup with portal carrier and parallel SCARA manipulator.

4.1 Portal Carrier

In order to provide the desired work space, the portal carrier has a size of approximately $5 \times 5 \times 2\,\mathrm{m}^3$. It has three translatory degrees of freedom, which are realized by three independent linear drives.

These linear drives are built using a commercially available carriage-on-rail system. The carriages are driven by a toothed belt. While the x- and y-axis consist of two parallel rails each for stability reasons, the z-axis is only a single rail. As a result, the system is driven by five three-phase AC-motors, that allow a maximum speed of $2\,\mathrm{m/s}$ and an acceleration of $2\,\mathrm{m/s}^2$. As the configuration space equals cartesian space, forward kinematics can be expressed by means of an identity matrix. Thus control is extremely easy to handle and very robust.

4.2 Parallel SCARA

The acceleration of the human hand is typically much higher than the acceleration of the portal carrier. In order to allow natural hand motion, a fast and lightweight kinematic is attached to the carriage of the z-axis. A two degree of freedom SCARA kinematic parallel to the x-y-plane is sufficient, as motion in z-direction is of minor importance. A SCARA kinematic covers planar motion, which can be described by means of polar coordinates.

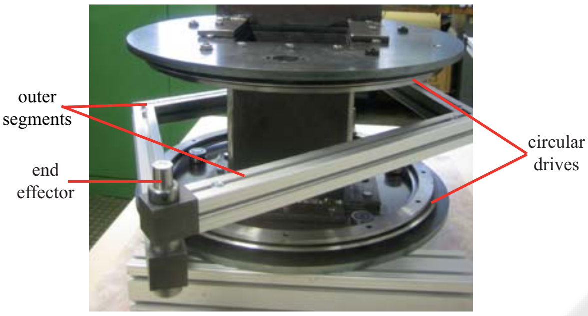


Figure 5: The parallel SCARA. The inner segments are replaced by circular drives. Work space was optimized by adding an additional angle to the outer segments.

We designed a parallel SCARA manipulator, which has the advantage, that both motors needed to drive the system can be integrated into the base. As a result, all moving joints are passive. This leads to a minimum of moving mass and thus better dynamics. In order to allow infinite circular motion, the inner segments have been replaced by circular drives, as shown in Fig. 5.

Although parallel SCARA devices have been used as haptic interfaces before (Campion et al., 2005), our approach is novel as the circular drives significantly reduce the complexity of the forward kinematics as both inner segments have their origin in exactly the same location.

The forward kinematics of the parallel SCARA are given as in Fig. 6, A, B and C are passive joints. Only the angles α and β are actively driven. The end-effector position C is given by

$$\underline{OC} = \begin{bmatrix} l_1 \frac{\cos(\alpha)+\cos(\beta)}{2} \\ l_1 \frac{\sin(\alpha)+\sin(\beta)}{2} \end{bmatrix} + \begin{bmatrix} \sqrt{l_2^2 \cos^2\left(\frac{\alpha+\beta}{2}\right) - \frac{(\sin(\alpha)+\sin(\beta))^2}{4}} \\ \sqrt{l_2^2 \sin^2\left(\frac{\alpha+\beta}{2}\right) - \frac{(\cos(\alpha)+\cos(\beta))^2}{4}} \end{bmatrix}, \qquad (1)$$

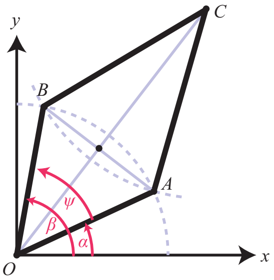


Figure 6: Kinematics of the parallel SCARA.

where $l_1 < l_2$ are the lengths of the inner and outer segments, respectively.

When attaching the parallel SCARA to the portal carrier, there is a redundancy that may be resolved by optimizing manipulability of the SCARA robot. The SCARA robot's manipulability is optimal when its radial travel is in center position. The SCARA robot's radial travel R is only dependent on the angle $\psi = \beta - \alpha$ and is given as

$$R = l_1 \cos\left(\frac{\psi}{2}\right) + \sqrt{l_2^2 - l_1^2 \sin^2\left(\frac{\psi}{2}\right)} . \qquad (2)$$

5 DISTRIBUTED ELECTRONICS

In order to control the haptic display at a high update rate, we designed a distributed electronic control system. This electronic system is not limited to control of the haptic display described in this paper, but it is modular and reconfigurable and can thus be fitted to any robotic system.

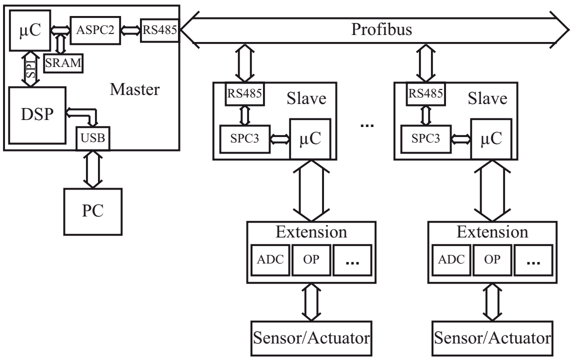


Figure 7: Structure of the control system.

As shown in Fig. 7 the control system consists of one master control node equipped with high processing power and a number of slave nodes, one for each sensor/actuator subsystem. These nodes are connected with PROFIBUS[1], which provides high bandwidth over long distances.

The master node shown in Fig. 8 on the left is equipped with an AD Blackfin DSP[2] header board (not shown) to provide enough processing power for control. On this DSP all sensor data is gathered and control outputs for all actuators are generated. The DSP is connected via the integrated serial port interface to a TI MSP 430 micro controller[3], that handles communication with the slave nodes. To communicate with the core of the telepresence system running on a standard PC, it also features a USB connection.

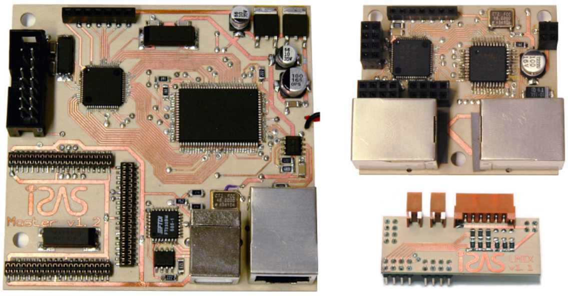


Figure 8: The master node (left), a slave node (top right) and the header board for one sensor (bottom right).

The slave node is a standardized unit, that is completely the same for all sensor/actuator subsystems. They are equipped with a TI MSP 430 micro controller, that has enough processing power to preprocess sensor data or to generate control signals for the actuator units.

The slave nodes are fitted to their specific task by adding an extension board, that provides the interfaces to the sensors and actuators, and by uploading the appropriate software. The right hand side of Fig. 8 shows a slave node and one extension board for a sensor system.

In general, each sensor and each actuator has its own slave node, because the distances between the subsystems are very large. However, if a sensor and the appropriate actuator are close to each other, it is possible to integrate both sensor pre-processing and actuator control on one slave node. This is the case for each of the SCARA robot's motors. Thus, it is possible to run inner control loops on these slave nodes.

6 SAFETY ARCHITECTURE

In order to prevent accidents when using the haptic interface a safety architecture was designed and implemented. This safety architecture consists of three levels to include various sources of failure.

The highest level is the *external level*. This level allows user inputs by means of emergency buttons and a dead-man-switch at the end-effector. This level also includes mechanical stop switches that prevent the system from destruction in case of a failure. If the *external level* detects a failure, it triggers the emergency stop program of all actuators and cycles down power. As the motors of the portal carrier have integrated power-off brakes, the system stops immediately.

On the *inter-node level* the nodes of the control system monitor each other. The master node constantly checks the alive status of all slave nodes based on timeouts. If any one of the nodes does not respond to the queries in time, an emergency stop is initiated. In order to also guarantee an emergency stop in case of a master failure, the actuator nodes stop the actuators immediately if the master node does not constantly refresh its commands.

On the *intra-node level* the components of each node monitor themselves and each other using their internal watchdog timers. In case of a malfunction, the node is stopped. This leads to a time-out on the inter-node level and eventually to an emergency stop.

7 CONCLUSIONS

In this paper we have presented our patent pending design of a novel haptic interface. This interface allows simultaneous wide area motion and haptic interaction. It consists of a parallel SCARA manipulator for precise haptic rendering and a portal carrier system that enlarges the work space to $4 \times 4 \times 2\,\mathrm{m}^3$ by pre-positioning the end-effector. As the portal carrier is driven by three linear drives, description of the systems kinematics is very simple. This makes it easy and robust to control.

We designed a distributed electronic control system based on Profibus that allows decentralized preprocessing of sensor data and control of actuators. A safety architecture that prevents accidents in case of malfunctions was implemented on the control system.

Although all components were developed specifically as extension to our extended range telepresence system, the concepts presented here are much more general and are not limited to the given application.

Future work will, of course, include finishing the setup of the hardware. While all components already exist, there is still some integration to be done. To

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[1] http://www.profibus.com/pb/

[2] http://www.analog.com/processors/processors/blackfin/

[3] http://www.ti.com/

prove the suitability of the concept, we will implement an impedance controller that allows haptic interaction with virtual environments. The envisaged controller will be based on decoupling haptic rendering and wide area motion by optimizing manipulability of the the haptic interface (Formaglio et al., 2005). However, in order to achieve the goal of telepresent manipulation with a real robotic teleoperator, more sophisticated control schemes might be necessary.

By adding haptics to our extended range telepresence system, all senses of interest will finally be telepresent. While users see and hear in the target environment, they receive proprioceptive feedback of their motion and have the possibility of haptic interaction during wide area motion. Thus the user is deeply immersed in the target environment and eventually identifies with the teleoperator.

This will lead to a new quality in robot teleoperation as users now have a truly intuitive interface to the robot and can fully focus on their task in the target environment.

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REFERENCES

Bakker, N. H., Werkhoven, P. J., and Passenier, P. O. (1998). Aiding Orientation Performance in Virtual Environments with Proprioceptive Feedback. In *Proceedings of the IEEE Virtual Reality Annual Intl. Symposium*, pages 28–33, Atlanta, GA, USA.

Bergamasco, M., Allotta, B., Bosio, L., Ferretti, L., Perrini, G., Prisco, G. M., Salsedo, F., and Sartini, G. (1994). An Arm Exoskeleton System for Teleoperation and Virtual Environment Applications. In *Proceedings of the IEEE Intl. Conference on Robotics and Automation (ICRA'94)*, pages 1449–1454, San Diego, CA, USA.

Borro, D., Savall, J., Amundarain, A., Gil, J. J., García-Alonso, A., and Matey, L. (2004). A Large Haptic Device for Aircraft Engine Maintainability. *IEEE Computer Graphics and Applications*, 24(6):70–74.

Bouguila, L., Ishii, M., and Sato, M. (2000). Multi-Modal Haptic Device for Large-Scale Virtual Environment. In *Proceedings of the 8th ACM Intl. Conference on Multimedia*, pages 277–283, Los Angeles, CA, USA.

Bunz, C., Deflorian, M., Hofer, C., Laquai, F., Rungger, M., Freyberger, F., and Buss, M. (2004). Development of an Affordable Mobile Robot for Teleexploration. In *Proceedings of IEEE Mechatronics & Robotics (MechRob'04)*, pages 865–870, Aachen, Germany.

Campion, G., Wang, Q., and Hayward, V. (2005). The Pantograph Mk-II: A Haptic Instrument. In *Proceedings of the IEEE Intl. Conference on Intelligent Robots and Systems (IROS'05)*, pages 723–728, Edmonton, AB, Canada.

Formaglio, A., Giannitrapani, A., Barbagli, F., Franzini, M., and Prattichizzo, D. (2005). Performance of Mobile Haptic Interfaces. In *Proc. of the 44th IEEE Conference on Decision and Control and the European Control Conference 2005*, pages 8343–8348, Seville, Spain.

Hoogen, J. and Schmidt, G. (2001). Experimental Results in Control of an Industrial Robot Used as a Haptic Interface. In *IFAC Telematics Applications in Automation and Robotics*, pages 169–174, Weingarten, Germany.

Nitzsche, N., Hanebeck, U. D., and Schmidt, G. (2004). Motion Compression for Telepresent Walking in Large Target Environments. *Presence*, 13(1):44–60.

Nitzsche, N. and Schmidt, G. (2004). A Mobile Haptic Interface Mastering a Mobile Teleoperator. In *Proceedings of IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, Sendai, Japan.

Richard, C. and Cutkosky, M. R. (1997). Contact Force Perception with an Ungrounded Haptic Interface. In *ASME IMECE 6th Annual Symposium on Haptic Interfaces*, Dallas, TX, USA.

Rößler, P., Beutler, F., and Hanebeck, U. D. (2005a). A Framework for Telepresent Game-Play in Large Virtual Environments. In *2nd Intl. Conference on Informatics in Control, Automation and Robotics (ICINCO 2005)*, volume 3, pages 150–155, Barcelona, Spain.

Rößler, P., Beutler, F., Hanebeck, U. D., and Nitzsche, N. (2005b). Motion Compression Applied to Guidance of a Mobile Teleoperator. In *Proceedings of the IEEE Intl. Conference on Intelligent Robots and Systems (IROS'05)*, pages 2495–2500, Edmonton, AB, Canada.

SensAble Technologies (1996). PHANTOM Haptic Devices. http://www.sensable.com/products/phantom_ghost/phantom.asp.

Stemmer, R., Brockers, R., Drüe, S., and Thiem, J. (2004). Comprehensive Data Acquisition for a Telepresence Application. In *Proceedings of Systems, Man, and Cybernetics*, pages 5344–5349, The Hague, The Netherlands.

Ueberle, M., Mock, N., and Buss, M. (2003). Towards a Hyper-Redundant Haptic Display. In *Proceedings of the International Workshop on High-Fidelity Telepresence and Teleaction, jointly with the IEEE Conference on Humanoid Robots (HUMANOIDS2003)*, Munich, Germany.

Unger, B. J., Klatzky, R. L., and Hollis, R. L. (2004). Teleoperation Mediated through Magnetic Levitation: Recent Results. In *Proceedings of IEEE Mechatronics & Robotics (MechRob'04), Special Session on Telepresence and Teleaction*, pages 1458–1462, Aachen, Germany.