Motion Compression for Telepresent Walking in Large-Scale Remote Environments

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ABSTRACT

Telepresent walking creates the sensation of walking through a target environment, which is not directly accessible to a human, e.g. because it is remote, hazardous, or of inappropriate scale. A mobile teleoperator replicates user motion and collects visual and auditory information from the target environment, which is then sent and displayed to the user. While walking freely about the user environment, the user perceives the target environment with the sensors of the teleoperator and feels as if walking through the target environment. Without additional processing of the user's motion data, the size of the target environment to be explored is limited to the size of the user environment. Motion compression extends telepresent walking to arbitrarily large target environments without making use of scaling or walking-in-place metaphors. Both travel distances and turning angles are mapped with ratio 1:1.

Keywords: Telepresence, Locomotion, Mobile Teleoperators, Virtual Environments

1. INTRODUCTION

Many applications of mobile robots still require the supervisory control of a human, in spite of the continued progress in the field of autonomous mobile robots. Consider for instance mobile robotic assistants for mine sweeping, nuclear cleanup, military reconnaissance or wood harvesting. Controlling the locomotion of these robots by means of joysticks is not intuitive and requires a lot of training.

A much more intuitive way is to track locomotion of a human operator (user) and to make the remote mobile robot (teleoperator) replicate this locomotion. At the same time, the teleoperator collects visual and auditory information from its environment (target environment) with a stereo camera pair and stereo microphones. The perceived sensory information is transferred back to the user environment and displayed to the user.

Such an extended area telepresence system provides the user with the feeling of actually walking through the target environment. The user not only perceives locomotion visually, as in the case of joystick control, but also with his/her proprioceptive, i.e., vestibular and kinesthetic, sensors. Proprioception is essential for the spatial perception of an environment and, hence, a prerequisite for navigation and wayfinding.[1]

If the locomotion of the teleoperator is an exact replica of user locomotion, the target environment, that can be visited, is limited to the size of the user environment. Such space restrictions either result directly from the size of the available user space or are caused by the limited range of the tracking system.

With Motion Compression (MC), we introduce a new paradigm, which allows to control the locomotion of a mobile teleoperator in arbitrarily large target environments by actually walking in a much smaller user environment. MC does, however, not make use of any scaling or of any walking-in-place metaphors. Rather, target environment locomotion is mapped to a corresponding locomotion path in the user environment which is of equal length and features the same turning angles when the user changes the direction of travel. The mapping

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is selected such that the degradation of realism, i.e., the inconsistency between visual and proprioceptive cues, is minimized.

MC is also very powerful for locomotion through large *virtual* environments. Especially when a good spatial perception of the virtual environment is required, MC can provide the necessary proprioceptive stimuli. Applications of MC combined with virtual environments include visiting virtual museums and virtual replications of possibly no longer existing historic buildings. An application with particular focus on gaining spatial knowledge are simulated emergency situation, where people are trained to find there way in and out of buildings.

Although scaling is not required to resolve the limitations caused by the size of the user environment, MC can be combined with scaling to make extremely small environments, e.g. biological systems, or extremely large environments, e.g. solar systems, accessible to human walking.

To unify the terminology, we introduce the term *proxy,* which stands for teleoperator in case of a real target environment and for avatar in case of a virtual target environment.

2. RELATED WORK

Teleoperated locomotion of mobile robots is addressed in a great variety of approaches.[2] Very few, however, aim at providing the user with a realistic sensation of locomotion.

Paulos et al.[3] developed an internet interface for control of a mobile teleoperator equipped with a camera, microphone, and speakers. Their goal is to create "tele-embodiment", i.e., the user identifies with the teleoperator.

Locomotion in large virtual environments, is the focus of a great number of research projects, too. Their goal is to design realistic interfaces, which create a "perfect" sensation of self-motion. Examples are 2D-treadmills[4, 5] or the tracking of physical user locomotion.[6, 7] A more abstract metaphor is to track physical in-place walking and stepping motion and to extract the user's intended locomotion therefrom.[8]

An approach quite similar to MC is taken by Razzaque et al.[9] However, they rely on a predefined path in the target environment and use rotational distortion mainly during phases of turning in place. Due to these deficiencies target environments cannot be arbitrarily large.

The effects of the various stimuli conveying information about self-motion on the human navigation and orientation capabilities have been studied by many researchers. The results of Bakker et al.[10] show that kinesthetic feedback among vestibular feedback and visual flow provides the most reliable and accurate data for path integration. Nevertheless, vestibular perception is essential for accurate path integration, too.[11, 12] The work of Chance et al.[13] suggests locomotion interfaces which use real translational and rotational user motion as input for tasks involving spatial orientation.

The human ability to detect the curvature deviation inherent to Motion Compression is related to the human vestibular and podo-kinesthetic sensation. Kolev et al.[14] found a detection threshold of $1.2°/s$ for rotational velocities detectable with the vestibular system. At an assumed walking speed of 1.0 m/s this value corresponds to a calculated curvature detection threshold of $1/50\ m^{-1}$.

3. WHY AND HOW MC WORKS

A human who is walking in a goal-oriented way performs path tracking control. The current position and orientation, which is continuously estimated from visual, auditory, and proprioceptive cues, is compared with the desired path and walking direction is adapted accordingly.

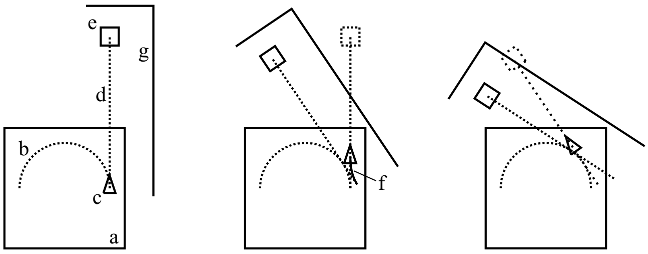
MC exploits this human path tracking behavior to *guide* the user on a path in the user environment (user path) which is a transformed version, i.e., an image, of the path the proxy travels in the target environment (target path). This is done by providing visual and auditory feedback from the target environment that influences the user's path tracking control in just that way.

Consider the example in Fig. 1. Straight line motion in the target environment is compressed into circular motion in the user environment.

(1) The user (c) is standing in the user environment (a) at the beginning of the user path (b), whereas the proxy (c) is at the beginning of the target path (d) in the target environment (g). Wearing an HMD, the user sees the goal object (e) in the target environment through the eyes of the proxy. Thus, user and proxy are coincident (c).

(2) The user has moved a short distance straight ahead in the direction which he/she saw the goal object in. However, the proxy's new position in the target environment reflects a circular motion (f) resulting in a deviation from the intended target path. The user now sees the goal object to his/her left hand side. This is the effect of MC and influences the user's path tracking control.

(3) The user compensates for the perceived deviation (path tracking control), turns left, and walks along the circular user path. The proxy travels on the straight target path.



(1) (2) (3)

Figure 1. User guidance as the basic principle of Motion Compression.

a ... user environment
b ... user path
c ... user/ proxy
d ... target path
e ... goal object
f ... proxy path increment
g ... target environment as seen by the user

Whereas the user's visual perception reflects the proxy's straight motion, the proprioceptive perception is consistent with the circular motion. A certain amount of inconsistency between vision and proprioception is tolerable, as experiments have proven, see Sec. 5. However, as the inconsistency becomes larger the user is more likely to notice a rotary motion of the target environment with respect to the user environment. This inconsistency is caused by the curvature deviation between target and user path.

4. MC ALGORITHM

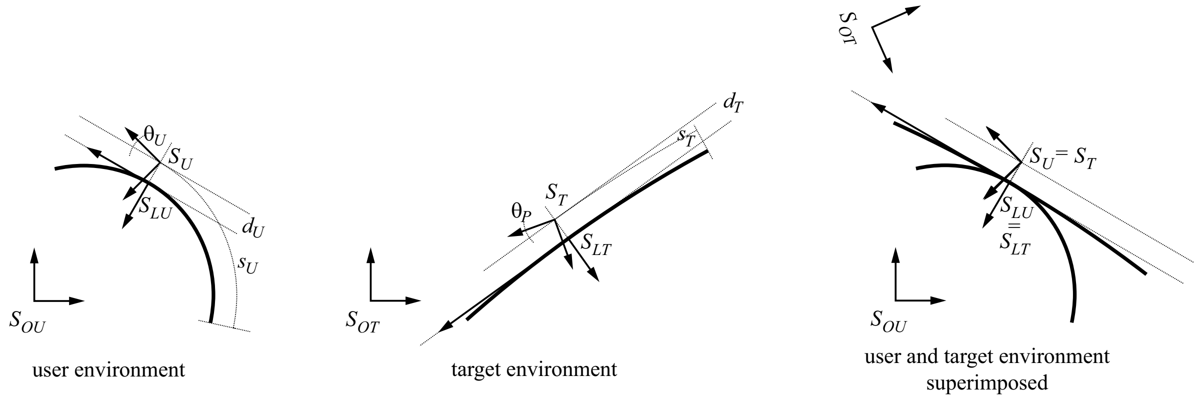
The MC algorithm comprises three main modules. First, the intended locomotion of the user in the target environment must be *predicted.* The result of *Path Prediction* is the target path. Second, the target path must be *transformed* such that its image fits into the available user environment. The result of *Path Transformation* is the user path. Third, the actual user motion in the user environment must be mapped to an actual proxy motion in the target environment such that the resulting visual and auditory sensations *guide* the user on the user path. This task is performed by *User Guidance* .

4.1. User Guidance

User Guidance does the actual mapping from a measured user position and orientation in the user environment to a desired proxy position and orientation in the target environment. This mapping is defined by the predicted target path, the corresponding user path, and the following properties:

(1) Positions on the user path are mapped to positions on the target path, with the distance the user moved along the user path (s_U) equal to the distance along the target path (s_T).

(2) Positions off the user path are mapped to positions off the target path, with the perpendicular distance from the user to the user path (d_U) equal to the distance of the proxy to the target path (d_T).



user environment

target environment

user and target environment superimposed

Figure 2. User guidance: The measured position and orientation of the user is mapped to the position and orientation of the proxy. Superimposing user and target environment illustrates the relationship between environments.

(3) User orientations tangential to the user path are mapped to proxy orientations tangential to the target path or more general the angle between user orientation and the tangent of the user path (θ_U) equals the angle between proxy orientation and target path (θ_T).

These properties are taken into account by introducing two local Cartesian coordinate frames S_{LU} and S_{LT} in addition to the world frame S_{OU} of the user environment and the world frame S_{OT} of the target environment. The origin of S_{LU} is on the user path at position s_U and its x-axis tangential to the user path. The origin of S_{LT} is on the target path at position $s_T = s_U$, see property (1) above, with its x-axis tangential to the target path, Fig. 2. From properties (2) and (3) above follows that position and orientation of the user (U) with respect to S_{LU} equals the position and orientation of the proxy (T) with respect to S_{LT}. Introducing homogeneous transformations to express position and orientation of one coordinate frame with respect to another, this can be written as

$$ {}^{LU}T_U = {}^{LT}T_T \ . \tag{1} $$

Assuming known transformations ${}^{OU}T_{LU}$ and ${}^{OT}T_{LT}$, the position and orientation of the proxy with respect to S_{OT} (${}^{OT}T_T$) are calculated from the measured position and orientation of the user with respect to S_{OU} (${}^{OU}T_U$) by

$$ {}^{OT}T_T = {}^{OT}T_{LT}\,{}^{LU}T_{OU}\,{}^{OU}T_U \ . \tag{2} $$

The transformation ${}^{OU}T_{LU}$ can be obtained from the measured position of the user in S_{OU} by dropping a perpendicular from the user position onto the user path. The foot of the perpendicular is the origin of ${}^{OU}T_{LU}$ and thus determines the path variable s_U, Fig. 2.

From equation (2), the transformation from user to target environment or vice versa is obtained as

$$ {}^{OT}T_{OU} = {}^{OU}T_{OT}^{-1} = {}^{OT}T_{LT}\,{}^{LU}T_{OU} \ . \tag{3} $$

This transformation describes position and orientation of the target environment with respect to the user environment, Fig. 2.

If user and target environment are superimposed according to this transformation, as in Fig. 2, user and proxy are coincident and the target path will always be tangential to the user path in the point specified by s_U. As the user moves along the user path, the target environment will move relative to the user environment in a way equal to the motion resulting from the target path rolling off the user path, see also Fig. 1.

If the curvatures of user and target path are equal, no relative motion of the two environments occurs. Visual and proprioceptive perception of locomotion will be consistent. The larger the deviation of curvature, the faster the target environment will turn relative to the user environment. The consistency between visual and proprioceptive perception is a function of the curvature deviation.

4.2. Path Transformation

The basic idea of Path Transformation is to take the target path and bend it such that it fits into the user environment. However, as we have shown in the previous subsection, curvature deviation between user and target path results in inconsistent visual and proprioceptive perception of locomotion and is experienced as a spinning motion of the target environment with respect to the user environment.

Therefore, Path Transformation is a dynamic optimization problem with the objective to minimize curvature deviation between target and user path. The path variable s is the independent variable and we consider the problem as not dependent on time and velocity.

The target path is given by the function

$$\kappa_T = \kappa_T\,(s) \quad s = 0 \ldots s_E \ , \tag{4}$$

where κ_T is the target path curvature, s the distance along the path and s_E the total length of the path. The optimal user path to be found will be given by the function

$$\kappa = \kappa\,(s) \quad s = 0 \ldots s_E \tag{5}$$

and its starting position and orientation

$$x_0 \ , \quad y_0 \ , \quad \varphi_0 \ . \tag{6}$$

An obvious objective functional for minimizing overall curvature deviation is

$$J_1 = \int_0^{s_E} \frac{1}{2} \left(\kappa - \kappa_T\right)^2 ds \ . \tag{7}$$

The user path is subject to the following equality constraints describing the relationship of curvature, orientation and position

$$\frac{dx}{ds} = \dot{x} \quad = \quad \cos\varphi \ , \tag{8}$$

$$\frac{dy}{ds} = \dot{y} \quad = \quad \sin\varphi \ , \tag{9}$$

$$\frac{d\varphi}{ds} = \dot{\varphi} \quad = \quad \kappa \ , \tag{10}$$

and a set of inequality constraints describing the feasible space in the user environment

$$\underline{g}(x, y) \geq 0 \ . \tag{11}$$

The terminal position and orientation of the user path may either be fixed or free. If free, the terminal position and orientation may be part of the optimization.

In general, the terminal position of the user path should be located as far away from the user environment boundaries as possible. This gives the user the freedom to set off in any direction from there. However, imposing a hard constraint for the terminal condition in many cases results in strongly curved paths. Therefore, a penalty term for the terminal condition is added to the objective functional according to

$$J_2 = J_1 + \Phi\left[x(s_E), y(s_E), \varphi(s_E)\right] \ . \tag{12}$$

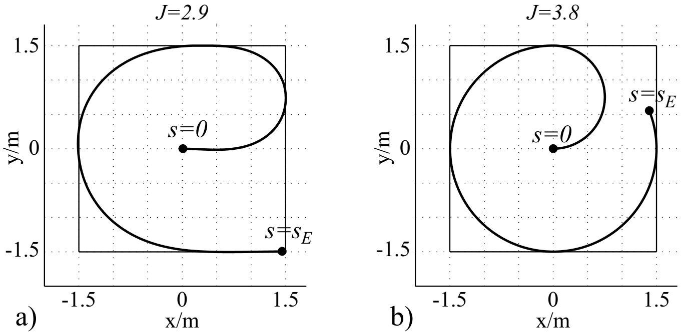


Figure 3. Sample solutions of path transformation: The target path is a straight line of 10 meters length, position and orientation of the endpoint are free, no penalty term is used. Sample a) is a numerical solutions of the dynamic optimization problem. Sample b) is the result of the Semicircle-Algorithm. J is the value of the objective function.

This general optimization problem for finding a user path with minimum curvature deviation can only be solved numerically, which so far could not be done sufficiently fast. Fig. 3a) shows a sample solution generated with DIRCOL.[15]

To reduce the computational effort, a heuristical algorithm was derived from the general optimization problem, which is fast enough to produce solutions online.

The general dynamic optimization problem defined above can be reduced to a form for which an analytic solution exists. This solution will then be used to find suboptimal solutions for the original problem.

Neglecting the inequality constraints in Eq. 11 and assuming the target path to be a straight line, i.e., $\kappa_T(s) = 0$, reduces the optimization problem to finding the minimum of

$$J_3 = \int_0^{s_E} \frac{1}{2}\dot{\varphi}^2 ds \quad . \tag{13}$$

By calculus of variation, the necessary condition for a minimum is given by

$$-\frac{d}{ds}\dot{\varphi} = -\frac{d^2\varphi}{ds^2} = 0 \quad . \tag{14}$$

Paths satisfying this equation are either circular arcs or straight lines. For that reason and because circles are convenient to deal with, path transformation is reduced to finding appropriate circular arcs. The target path is incrementally transformed to a chain of circular arcs.

The following assumptions are the basis for the heuristic algorithm:

(1) The predicted path is a straight line starting at the proxy's position.
(2) The predicted path has no fixed endpoint.
(3) The user environment is a convex polygon.

Then the user path is a circular arc satisfying the following conditions:

(1) The starting point is the user position.
(2) The starting direction coincides with the direction of the target path mapped into the user environment.
(3) The arc belongs to the *largest semicircle* fitting into the user environment boundaries.

Fig. 4 gives some examples of largest semi-circles with varied user positions and target path directions in a square user environment.

Although not rigorously proven yet, simulations of the Semicircle-Algorithm lead to the conclusion that, for straight target paths of sufficient length, the resulting user paths always converge to the maximum inscribed

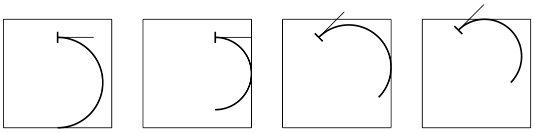


Figure 4. Largest semicircles fitting into a square user environment for different given starting positions and directions.

circle of the user environment Fig. 5. This property is very favorable if the predicted path in fact is a straight line and no change of direction must be expected. In this case, the maximum inscribed circle of the user environment is the optimal user path with minimum curvature.

However, the endpoint of a user path created with the Semicircle-Algorithm is very likely to be close to the boundaries of the user environment. This severely increases the curvature of the subsequent user path, if the user continues the walk in a direction perpendicular to the boundary.

Two alternative extensions to the Semicircle-Algorithm have been developed to remedy this disadvantage. Their common goal is to place the endpoint of the user path close to the center of the user environment. The first extension uses a contracted model of the user environment for path transformation with the amount of contraction being zero at the beginning of the path and increasing towards the end. The second extension continuously checks, if there exists a suitable circular arc, that places the endpoint of the user path in the center of the user environment and uses this arc instead of the largest semicircle.

Fig. 3 shows a user path created with the Semicircle-Algorithm. The target path is a straight line with a length of 10 m. The transformation was achieved by successively transforming fractions of 1 cm length. Comparison with the numerical solution of the dynamic optimization problem reveals a higher value of the objective function, i.e., the Semicircle-Path has larger overall curvature. However, the Semicircle-Algorithm can be executed incrementally, which is an advantage over the numerical algorithm.

In the experimental setup, the Semicircle-Algorithm is executed concurrently with user tracking at 50 Hz. A new circular arc is determined with every new measurement from the tracking system and every update of the predicted target path. Thus, the user path is planned incrementally and not in advance. Nevertheless, the semicircle-algorithm features a predictive behavior which is achieved by using semicircles whose sizes are influenced by the boundaries of the user environment before the user actually reaches them.

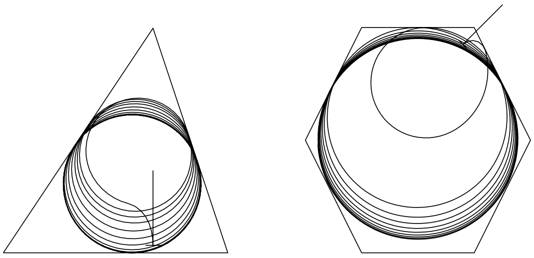


Figure 5. User paths planned with the semicircle-algorithm in two different convex user environments. For sufficiently long straight target paths, the resulting user path converges to the maximum inscribed circle of the user environment polygon, which in fact is the path of minimum curvature.

4.3. Path Prediction

Both the Path Transformation module and the User Guidance module require information about the path the user is about to walk along in the target environment. This information is provided by the Path Prediction module. It processes user motion data and, optionally, uses model information of the target environment to predict future locomotion of the user.

Two approaches for path prediction are distinguished. First, a path prediction algorithm can be based on current and past position/orientation data of the proxy. Such an algorithm would then make use of some model of human locomotion to predict future motion. It is obvious that this locomotion based approach can only offer short term prediction as long as the locomotion model does not supply information about the users global goal of locomotion. Second, long term prediction is possible if the users intention to head for a particular point or landmark in the target environment can be recognized. Intention recognition must be based on a model of the target environment from which information about potential goals of locomotion can be extracted.

The locomotion based approach can be applied to structured as well as unstructured target environments because it does not rely on any information about the target environment. This is advantageous in the case of real target environments which are to be explored by means of a mobile teleoperator like in military reconnaissance applications. However, this approach can not predict sudden changes of direction. Thus, if locomotion based prediction is employed, the Path Transformation module must always try to keep the user path away from the user environment boundaries. This results in higher overall curvature.

Target based path prediction provides more information about the user's future locomotion. However, it can only be applied if a model of the target environments is available, which is naturally the case with virtual environments.

Using a target environment model, the target based approach can predict further into the future. Once the algorithm has recognized the user's intention to walk up to a particular object, a predicted path of a few meters length may be the result. This predicted path may include, unlike the locomotion based prediction, on-the-spot-turns which can then be considered in the Path Transformation Module. In addition, a target based prediction usually gives information about the ultimate goal of the path. Assuming that the user stays on the path until he/she reaches the goal, the goal is the only part of the path where unpredicted changes of direction may occur. Thus, only the end point of the path has to be transformed to a location in the user environment with clearance from its boundaries in order to avoid strong curvature when the user starts out from there. This results in a considerable reduction of overall curvature.

Both a locomotion based and a target based algorithm have been implemented and tested successfully. The locomotion based algorithm rests on the following simple model of human locomotion: "future walking direction equals gaze direction." In this case, the predicted path is always a straight line starting at the proxy's position and running in the direction of its gaze. The endpoint of the predicted path is undetermined. Thus, a corresponding path transformation algorithm cannot optimize the endpoint of the user path but must anticipate unpredicted changes of direction.

The implemented target based algorithm is equally simple. From the model, objects of interest are identified offline and manually as potential goals of locomotion. One of these potential goals is then selected online as the endpoint of the predicted path. The selection is based again on gaze direction. The longer the user remains looking at a potential goal, the more likely the object is the user's goal. This likelihood is expressed by a coefficient $w_i \in [-1; 1]$ assigned to every potential goal. w_i is increased when the corresponding object is within the field of view and decreased otherwise. The object with the largest coefficient w_i is selected and the predicted path is given by the straight line from the user to the selected goal. With this prediction algorithm optimization of the user path endpoint becomes feasible.

Path prediction is performed concurrently with user tracking. The predicted target path is updated at a rate of 50 Hz with every incoming position and orientation measurement.

5. EXPERIMENTAL VALIDATION

MC has been evaluated with both virtual and real target environments. In either case, the user environment was a 4 m by 4 m square room, Fig. 6. The usable area was limited to 3 m by 3 m to give some safety margin to the physical walls. The user's motion was tracked by an Ascension Motion Star magnetic tracking system,[16] whose sensors provide position and orientation data in all six degrees of freedom. For visual and auditory feedback, the head mounted display V8 by Virtual Research Systems, Inc.[17] was employed.

Figure 6. User environment for MC experiments. The user wears a head mounted display. Head motion is tracked by a magnetic tracking system.

5.1. Maximum Unnoticed Curvature

MC introduces inconsistency between the visual and the proprioceptive sensation of locomotion. As stated in Sec. 3, the inconsistency is caused by the curvature deviation between user and target path. The objective of the experiment reported on in this subsection was to find the maximum curvature deviation that goes unnoticed by the user.

The experiment was performed in a virtual environment comprised of just a large green plane with a white line and marked end points. The test person was asked to walk back and forth between the end points along the straight line. Thus, the target path of each individual trial was by construction a straight line. The corresponding user paths were circular arcs of curvatures randomly varying from $-0.2\ m^{-1}$ to $0.2\ m^{-1}$. After each trial the test person was asked to report whether the user path was curved left or right.

Fig. 7 shows the relative frequency h of correctly detected direction of curvature as a function of the curvature κ. It is obvious, that for curvatures $\kappa < 0.1\ m^{-1}$ the test person is no longer able to detect the direction of curvature with 100% certainty. Therefore, we use $\kappa = 0.1\ m^{-1}$ as the perceptual threshold for curvature deviation, which corresponds to a radius of 10 m. Details of the experiment with a more in depth discussion of the results will be published elsewhere.

5.2. Virtual Museum

The MC algorithm is applied to visiting a large room in a virtual museum. The size of the virtual target environment is 30 m by 20 m. Fig. 8 shows a screen shot of the virtual museum. Although the available user environment is 3 m by 3 m only and thus user path curvature is usually greater than $0.3\ m^{-1}$, strolling

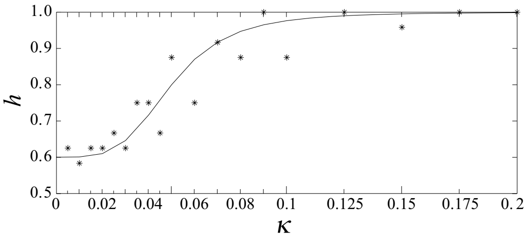


Figure 7. Relative frequency h of correctly detected direction of curvature as a function of curvature κ.

through the virtual museum is found very comfortable and intuitive by most test subjects. As long as the user decides for one piece of art and walks there straight ahead, no peaks of curvature deviation occur and subjects quickly accustom to the inconsistency of visual and proprioceptive perception. Test persons are observed to reach normal walking speed after a few cautious initial steps. However, peak curvature and changes of direction of curvature are likely to occur when the user decides for a new goal of locomotion at some unfavorable position. The inconsistency, although soon becoming almost unnoticeable, causes slight motion-sickness in some subjects.

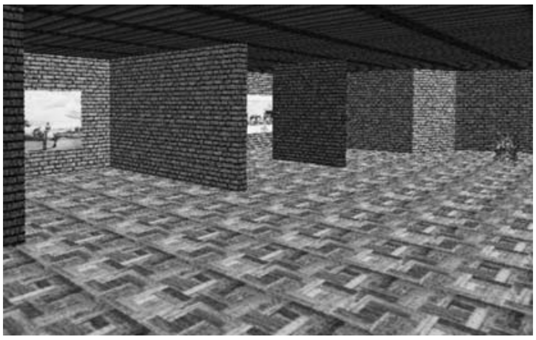


Figure 8. Screen shot of the virtual museum.

5.3. Controlling a Mobile Teleoperator

The MC algorithm is applied to control locomotion of a mobile teleoperator. The mobile teleoperator is based on a four-wheel omnidirectional platform[18] and is equipped with a stereo camera pair mounted on a pan-tilt-roll head.[19] From within the 3 m by 3 m user environment, the user can "walk" the teleoperator through several rooms of the laboratory, see Fig. 9.

Figure 9. Wheel-based mobile teleoperator with stereo camera unit.

Motion of the user is tracked with two magnetic sensors, one at the user's head and one at the hip. Platform locomotion is controlled by the user's hip motion, whereas the orientation of the camera pair is controlled by the user's head orientation.

The User Guidance Module, whose task is to calculate proxy positions and orientations from the measured user positions and orientations, generates reference values for the mobile teleoperator. The teleoperator follows these reference values with some delay, due to its dynamic properties. This delay is part of the user's path tracking control loop. Therefore, MC-ed locomotion through real target environments is not as intuitive as in the case of virtual target environments, where the delay between user action and corresponding feedback from the target is much smaller. In some cases, test people had problems relating the perceived teleoperator motion to their own motion. However, the delay in the visual feedback can be eliminated by panning and zooming the captured images according to the control error of the teleoperator.

All position and orientation data of the teleoperator is expressed in a platform fixed coordinate system. Transforming positions and orientations from a world coordinate system to the moving platform frame effectively results in commanding position and orientation increments rather than absolute positions and orientations. This eliminates the necessity of global localization of the teleoperator.

6. CONCLUSION

Motion Compression (MC) is a novel method for compressing large scale voluntary locomotion into much smaller available spaces. The method is capable of mapping distances and turning angles with ratio 1:1 and does *not* rely on scaling. It can, however, be combined with scaling in order to magnify or reduce target environments which otherwise would not be accessible by human walking. Consider for instance walking through a biological cell or through a solar system.

The advantage over conventional interfaces for locomotion in virtual or remote real environments (target environments) is that MC provides the “feeling” of motion by approximating proprioceptive cues. The visual sensation is consistent with motion in the target environment, whereas the proprioceptive sensation is consistent with the physical motion of the user. Due to the modification of path curvature, this proprioceptive sensation is just an approximation of the locomotion in the target environment.

Experiments in virtual target environments demonstrated, that even user environments as small as 4 m by 4 m are sufficient for walking through large virtual halls with great realism. However, when MC is employed to control mobile teleoperators in real target environments, the time delay introduced by the dynamics of the teleoperator's position control reduces realism.

MC is introduced for general unstructured target environments as well as target environments satisfying certain prerequisites. In any case, MC comprises three main components: (1) estimation/recognition of intention for predicting future locomotion of the user, (2) transformation of the predicted path into the limited user environment, and (3) tracking the user's physical motion and mapping it to the target environment. Mapping user motion to the target environment is performed in such a way that the resulting visual cues affect the user's path tracking control, thus guiding the user on the transformed path.

In the future MC will be extended to 3D environments including stairs, ladders, and slopes. Another goal is to share the user environment with its infrastructure (floorspace, tracking system, ...) among several users. Path transformation in this multi-user scenario not only has to consider the boundaries and static obstacles of the room but must also provide reliable user-to-user collision avoidance measures.

With respect to the path prediction and transformation components, stochastic processing promises a substantial increase of performance. The current implementation relies on just a single predicted path. If that prediction proves to be wrong, degradation of realism is very likely due to strong curvature.

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REFERENCES

1. R. P. Darken, “Spatial Orientation and Wayfinding in Large-Scale Virtual Spaces II,” *Presence* **8**, pp. iii–vi, Dec. 1999.
2. T. Fong and C. Thorpe, “Vehicle Teleoperation Interfaces,” *Autonomous Robots* **11(1)**, Jul. 2001.
3. E. Paulos and J. Canny, “Designing Personal Tele- Embodiment,” in *Proceedings of the IEEE International Conference on Robotics & Automation*, pp. 3173–3178, 1998.
4. H. Iwata, “Walking About Virtual Environments on an Infinite floor,” in *Proceedings of the Virtual Reality Conference*, pp. 286–293, (Houston, Texas), 1999.
5. R. P. Darken, W. R. Cockayne, and D. Carmein, “The Omni-Directional Treadmill: A LocomotionDevice for Virtual Worlds,” in *Proceedings of the ACM UIST*, pp. 213–222, (Alberta, Canada), 1997.
6. G. Welch, G. Bishop, L. Vicci, S. Brumback, K. Keller, and D. Colucci, “High-Performance Wide-Area Optical Tracking - The HiBall Tracking System,” *Presence* **10**, pp. 1–21, Feb. 2001.
7. N. Nitzsche, U. D. Hanebeck, and G. Schmidt, “Mobile Haptic Interaction with Extended Real or Virtual Environments,” in *Proceedings of the IEEE International Workshop on Robot-Human Interactive Communication*, pp. 313–318, (Bordeaux/ Paris, France), 2001.
8. M. Slater, M. Usoh, and A. Steed, “Steps and Ladders in Virtual Reality,” in *Proceedings of the ACM Conference on Virtual Reality Software and Technology*, pp. 45–54, (Singapore), 1994.
9. S. Razzaque, Z. Kohn, and M. C. Whitton, “Redirected Walking,” in *Proceedings of EUROGRAPHICS*, 2001.
10. N. H. Bakker, “The Effect of Proprioceptive and Visual Feedback on Geographical Orientation in Virtual Environment,” *Presence* **8**, pp. 36–53, Feb. 1999.
11. W. Becker, G. Nasios, S. Raab, and R. Jürgens, “Fusion of Vestibular and Podokinesthetic Information during Self-Turning towards Instructed Targets,” *Exp Brain Res* , pp. 458–474, Jan. 2002.
12. S. Glasauer, M.-A. Amorim, I. Viaud-Delmon, and A. Berthoz, “Differential effects of labyrinthine dysfunction on distance and direction during blindfolded walking of a triangular path,” *Exp Brain Res* (145), pp. 489–497, 2002.
13. S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis, “Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration,” *Presence* **7**, pp. 168–178, Apr. 1998.
14. O. Kolev, T. Mergner, H. Kimming, and W. Becker, “Detection thresholds for object motion and self-motion during vestibular and viso-motor stimulation,” *Brain Res Bull* (40), pp. 451–457, 1996.
15. O. von Stryk, *User’s Guide for DIRCOL: A Direct Collocation Method for the Numerical Solution of Optimal Control Problems*. Lehrstuhl für Höhere Mathematik und Numerische Mathematik, Technische Universität, München, 2.1 ed., 1999.
16. “http://www.ascension-tech.com.”
17. “http://www.virtualresearch.com/products/v8.htm.”
18. U. D. Hanebeck and N. Šaldic, “A Modular Wheel System for Mobile Robot Applications,” in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 17–23, (Kjongju, Korea), 1999.
19. H. Baier, F. Freyberger, and G. Schmidt, “Interaktives Stereo-Telesehen - Ein Baustein wirklichkeitsnaher Telepräsenz,” *at Automatisierungstechnik* **49**, pp. 295–303, Jul. 2001. Oldenbourg Verlag München.