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(54) DRIFT-BASED ADAPTIVE WORKSPACE MAPPING CONTROLLER IN HAPTIC INTERACTION

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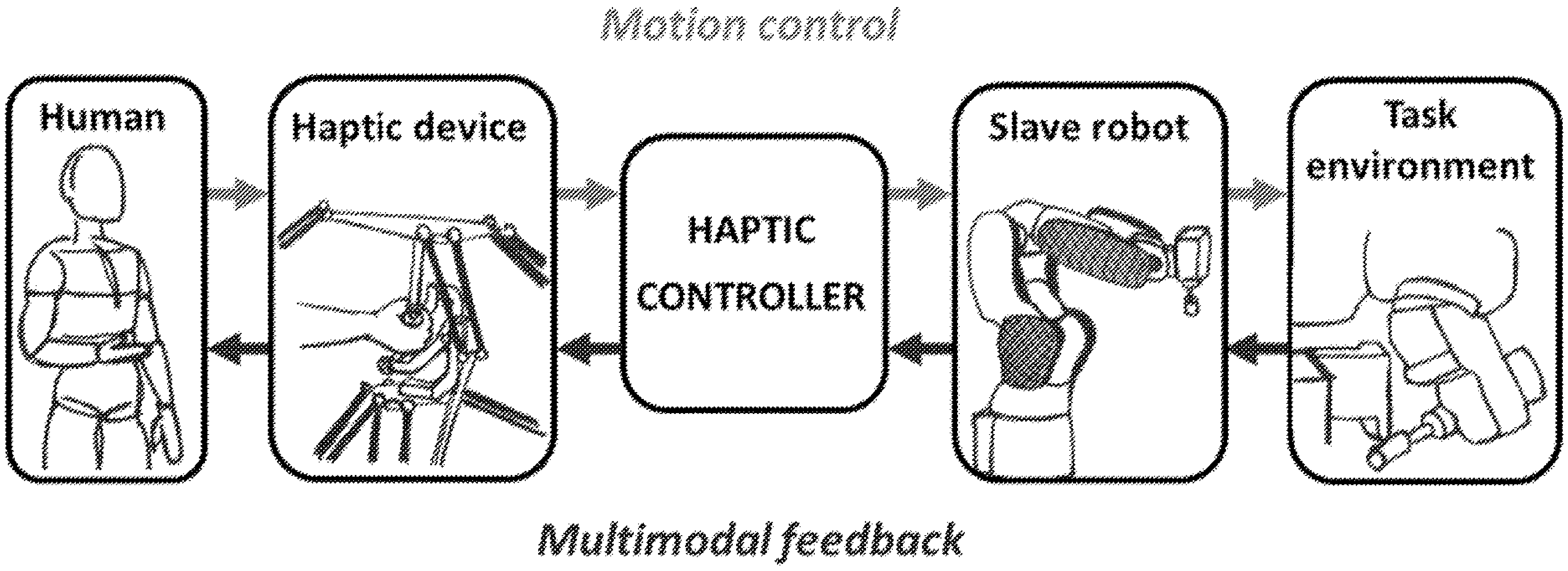
(57) ABSTRACT

An adaptive workspace mapping controller is provided having a fine balance between a progressive drift to the task area of interests and an adjustment of the remote force-motion resolution through scaling factor change. This adaptive workspace mapping controller gives the human the possibility to perform teleoperation activities in any environments without feeling the limitations of the haptic interface. Embodiments smartly and continuously adapts force-motion mapping in the teleoperation system, between the haptic device and the controlled robot, with respect to their respective workspaces and capabilities, to the task trajectories and interaction forces, and to user preferences. It significantly improves on the existing mapping controllers since the new drift-computation method and the additional adaptive-scaling step make it as efficient in large free-space motions as in quasi-static interaction tasks.



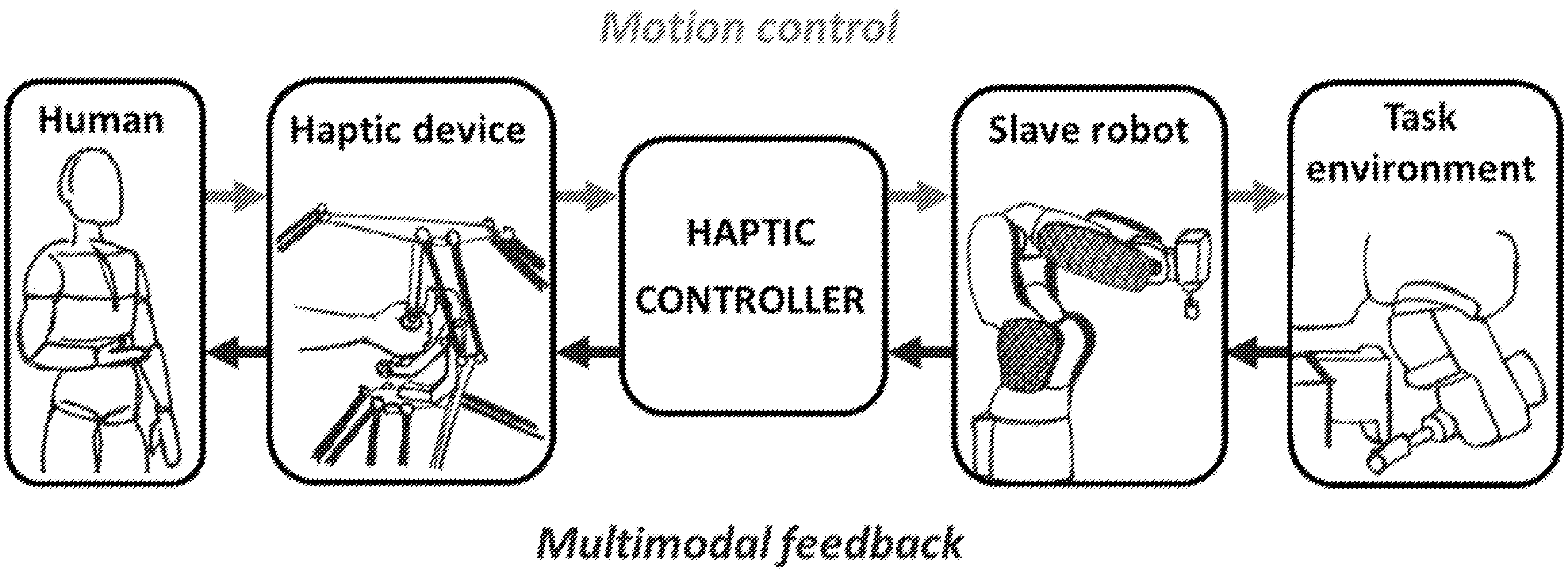

Motion control
Human
Haptic device
HAPTIC CONTROLLER
Slave robot
Task environment
Multimodal feedback

FIG. 1

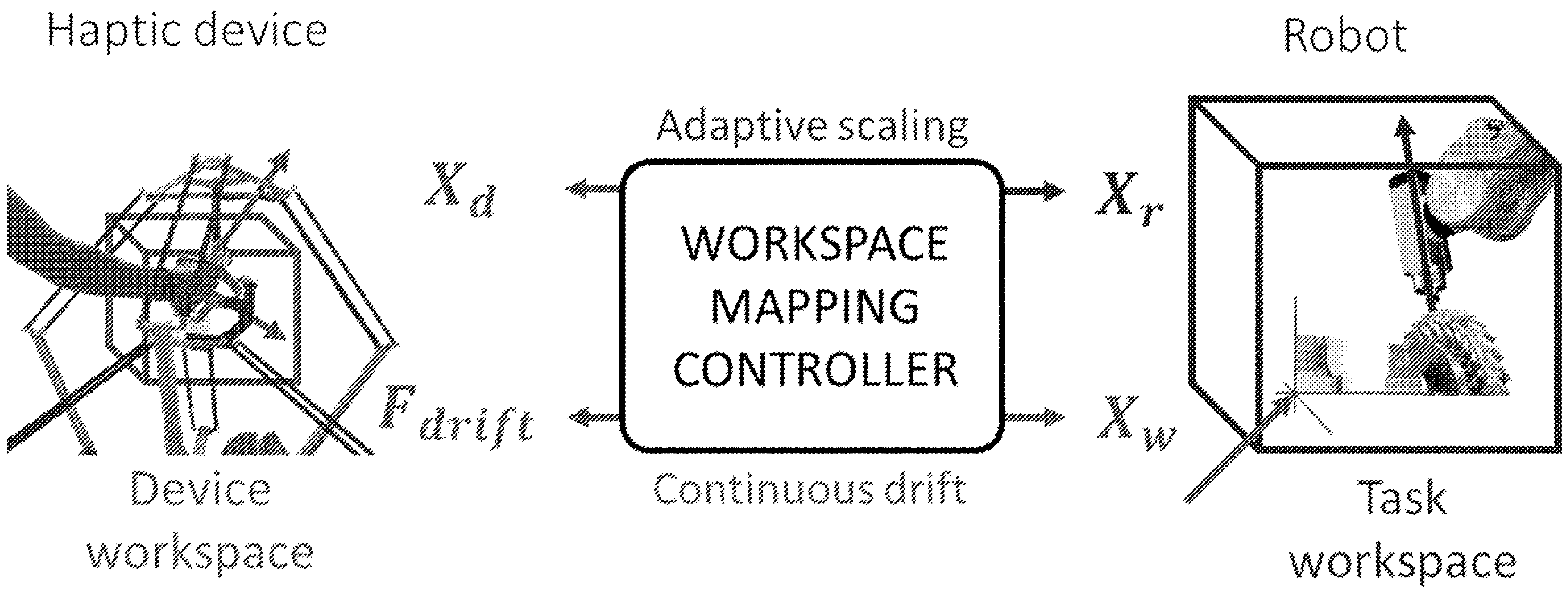

Haptic device
Robot
Adaptive scaling
X_d
WORKSPACE
MAPPING
CONTROLLER
X_r
F_{drift}
X_w
Device
workspace
Continuous drift
Task
workspace

FIG. 2

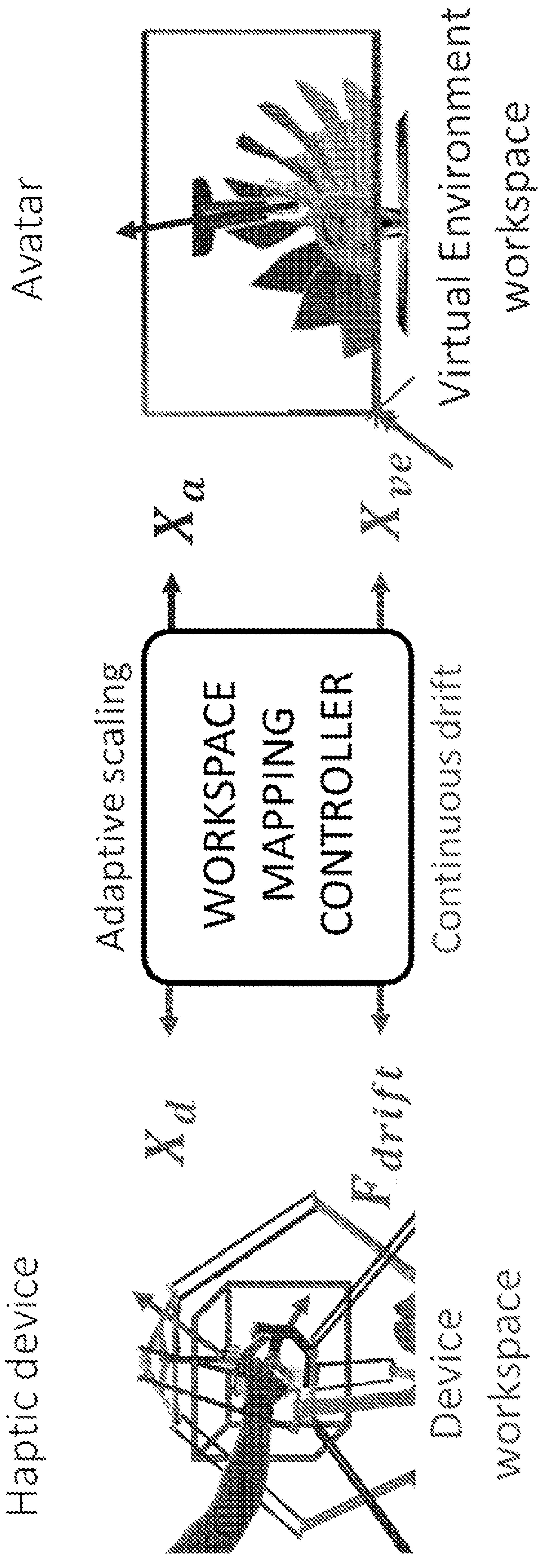

Haptic device
Device workspace
X_d
F_{drift}
Adaptive scaling
WORKSPACE MAPPING CONTROLLER
Continuous drift
X_a
X_{ve}
Avatar
Virtual Environment workspace

FIG. 3

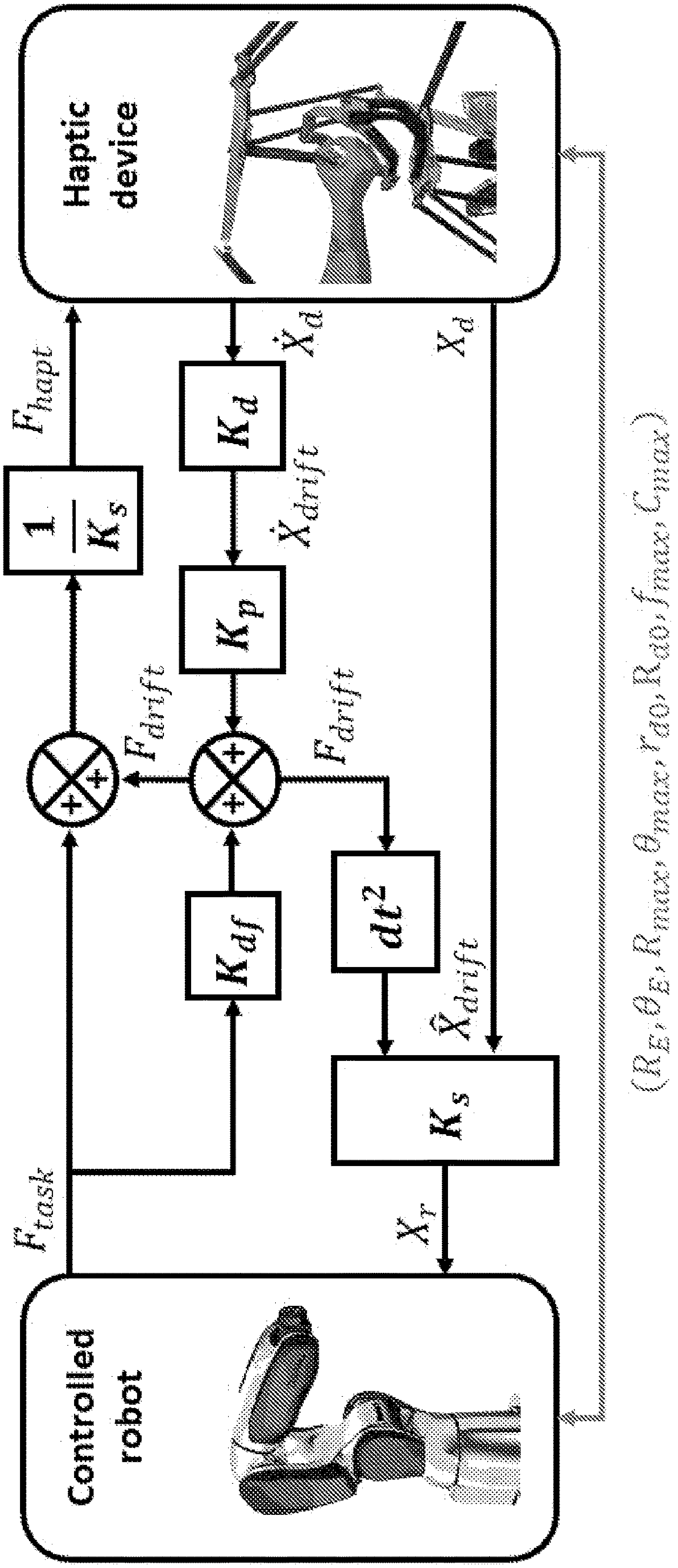

Haptic device
Controlled robot
F_{hapt}
$\frac{1}{K_s}$
K_d
K_p
K_{df}
dt^2
K_s
$\dot{X}_d$
$\dot{X}_{drift}$
$\ddot{X}_{drift}$
X_d
X_r
F_{drift}
F_{drift}
F_{task}
+
+
+
+
$(R_E, \theta_E, R_{max}, \theta_{max}, r_{d0}, R_{d0}, f_{max}, C_{max})$

FIG. 4

DRIFT-BASED ADAPTIVE WORKSPACE MAPPING CONTROLLER IN HAPTIC INTERACTION

FIELD OF THE INVENTION

[0001] This invention relates to controllers for haptic devices.

BACKGROUND OF THE INVENTION

[0002] Teleoperation is a key aspect of collaborative robotics allowing the human to safely achieve remote tasks in manifold activity areas such as industry, medical, space, or entertainment. The human operates a distant robot (or a virtual avatar) through a teleoperation system, the haptic device, which replicates the sense of touch from the interaction between the robot and the environment. A proper adaptive mapping between the workspaces of the haptic device and the controlled robot, in terms of motion and force, is crucial to ensure remote task performances. Whatever the size of the task environment, the required precision, or the level of force feedback, the human operator should be able to intuitively achieve his/her activity. The present invention addresses the challenges of force/motion mapping in haptic teleoperation and describes a novel adaptive workspace mapping controller.

SUMMARY OF THE INVENTION

[0003] The present invention addresses current issues of haptic-robot workspace mapping and provides a dynamically adaptive workspace mapping controller effective in any haptic teleoperation applications. The controller maps the positions and forces between the haptic device and the controlled robot (or the virtual avatar) and aims at being intuitive and imperceptible to the user. The workspace mapping controller combines a drift algorithm, continuously moving the haptic device back to its workspace center and the robot to the task area of interests, and a smart adaptive scaling of the exchanged motions and forces. Components of the workspace mapping controller are:

- **[0004]** In one example, the scaling factor which is being varied according to the distance to the workspace boundary to adjust the remote task resolution. Indeed, in coarse and free-space motions, the drift is light, and the user could quickly approach the device workspace boundary. Increasing the scaling factor with respect to the distance to the workspace center prevents the user to reach the workspace limits anytime while exploring the entire task environment. When performing fine tasks in a small area of interests, the drift brings the haptic device back to its center and the scaling factor goes down to 1 (or less), which gives a good accuracy to the user. This ranging can be straightly proportional to the distance or varied in different ways. For example, one could choose to implement a ballistic technique to adjust the scaling factor with respect to the haptic device velocity. The technical contributions are that the workspace boundaries cannot be reached or interfere with the user motion, and that the precision of the controlled robot is varying to be consistent with the task demand.
- **[0005]** In another example, the controller is extended to manage 6-degree-of-freedom tasks in any environment. The only task-dependent parameters which must be set to adapt the scaling are the size of the task workspace and the desired precision. Therefore, the workspace mapping controller is versatile and suitable for any haptic application.
- **[0006]** In still another example, a drift-based technique progressively relocates the haptic and robot workspaces toward the task center. The initial definition of the drift velocity was given as the product of the haptic device instant velocity with the offset position of the device with respect to its center. This formulation enables to drift back to the center location only in presence of input motions from the user. However, the drift occurs and pulls the user back to the center of the workspace regardless the direction of motion or the interaction forces with the environment. The user may perceive a parasitic force component inconsistent with the task interactions and the method is inefficient in quasi-static tasks. A major technical improvement of the present invention is to consider the task interactions to adapt the drift factor of the haptic device. To this end, the drift velocity has an additional component computed from the interaction force and becomes, therefore, consistent with the expected haptic feedback from the task environment. This projection removes parasitic force artifacts which would interfere with the task perception and makes the drift technique effective in quasi-static tasks.
- **[0007]** In still another example, the controller integrates the haptic device capabilities (workspace size, maximum force feedback, or the like) to adapt the drift and scaling parameters to different hardware.
- **[0008]** In still another example, a user tunes the acceptable level of drift, defined as the percentage of drift force over the force feedback and device current velocity. This setting parameter of the controller makes the controller easy to use while staying flexible and suitable to different user preferences.
- **[0009]** In still another example, the invention is a drift-based adaptive workspace mapping controller for haptic applications. This controller has a (i) robot controller, (ii) a haptic device controller, and (iii) a haptic-robot interaction controller which has a control strategy which combines a drift-based approach and an adaptive scaling to map exchanged force and motion data from one robot space to a haptic device space. Further, the haptic-robot interaction controller has hardware and task input parameters, defined as a haptic device workspace size, a maximum force feedback, a size of the task workspace, and user preferences, given through a percentage of acceptable drift force over a force feedback and a percentage of acceptable drift velocity over the device instantaneous velocity, which adjust a workspace mapping to a teleoperation system.
- **[0010]** In yet another example, the invention is a control method of workspace mapping for haptic-robot or haptic-avatar interactions. Having (i) a robot or a virtual avatar of the robot, and (ii) has a haptic device, the method controls haptic-robot interactions or haptic-avatar interactions, where the control includes calculating and applying an adaptive scaling factor to exchanged forces and motions in the haptic-robot interactions or the haptic-avatar interactions, where the adaptive scaling factor is based on a task accuracy and an environment size in which the task is performed.

The method further computes and applies a drift force to move the haptic device at its workspace center and to relatively move the robot to the task area of interest, where the drift factor is based on a haptic device velocity and a task interaction force.

[0011] The adaptive workspace mapping controller according to embodiments of this invention is a fine balance between a progressive drift to the task area of interests and an adjustment of the remote force-motion resolution through scaling factor change. This mapping controller gives the human the possibility to perform teleoperation activities in any environments without feeling the limitations of the haptic interface.

[0012] Embodiments of the invention smartly and continuously adapts force-motion mapping in the teleoperation system, between the haptic device and the controlled robot, with respect to their respective workspaces and capabilities, to the task trajectories and interaction forces, and to user preferences. It significantly improves on the existing mapping controllers since the new drift-computation method and the additional adaptive-scaling step make it as efficient in large free-space motions as in quasi-static interaction tasks.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** shows according to an exemplary embodiment of the invention the haptic teleoperation scheme. Teleoperation allows human operators to safely achieve remote tasks thanks to a haptic device. The haptic device replicates the physical interactions between the robot and the task environment through multimodal feedback.

[0014] FIG. **2** shows according to an exemplary embodiment of the invention the implementation of the workspace mapping controller to handle haptic-robot interactions in teleoperation applications. The controller has two main components: a drift model which continuously moves the haptic device and robot workspaces towards the task area of interest and an adaptive scaling factor applied to the exchanged forces and motions to adjust the remote task resolution. It, therefore, both increases the haptic-robot precision to control and perceive task interactions in the main operating area and enables large free-space motions without reaching the device workspace limits.

[0015] FIG. **3** shows according to exemplary embodiments of the invention the implementation of the workspace mapping controller to handle haptic-avatar interactions in virtual environments. The extension of the controller to virtual haptic interactions is straightforward. The combined adaptive scaling and drift technique smartly map force and motion data between the haptic device and the simulated world. The mapping algorithm adapts to any haptic device, robot, or task requirements.

[0016] FIG. **4** shows according to an exemplary embodiment of the invention the workspace mapping controller bloc diagram. To perform remote tasks in any environment without feeling the hardware limitations, the workspace mapping controller combines a progressive drift to the task area of interest with a smart adjustment of the scaling factor refining the task resolution. The scaling and drift parameters are computed with respect to the task requirements and haptic device constraints. User preferences can be simply set through the acceptable level of drift and the desired maximal resolution.

DETAILED DESCRIPTION

[0017] The problem this invention addresses considers a standard bilateral teleoperation scheme, as shown in FIG. **1**. The human operator controls the motion of a slave robot thanks to the haptic device to perform his/her activity in the task environment. The interaction between the robot end-effector and the task environment are sensed and transferred to the operator through multimodal feedback. In virtual applications, the slave robot is replaced by an avatar performing tasks in a virtual environment.

[0018] A proper motion/force mapping between the workspaces of the haptic device and the controlled robot is crucial to achieve good performances in the remote task and is the objective of this invention. FIG. **2** and FIG. **3** show the main features of the workspace mapping controller, respectively in haptic-robot teleoperation and in simulation of a virtual avatar. The haptic device position X_d is imposed by the human operator within the available degrees of mobility. The controller can manage commands in 6 degrees of freedom—position and orientation of the end-effector. The set robot position X_r with respect to its workspace center X_w—or respectively the set avatar position X_a with respect to the virtual environment center X_{ve}—is computed by the workspace mapping controller. The reverse transformation is applied to the force sent from the robot sensory observation to the haptic device. The controller combines an adaptive scaling factor K_s with a drift of the haptic device to its workspace center. The haptic device drift induces a related shift of the robot workspace center X_w to the task area of interest.

[0019] The workspace mapping controller has been adapted for easier use while staying flexible and suited to any haptic device and to perform any task. The input parameters of the controller are the haptic device performances—device workspace size (R_{max}, θ_{max}) and maximum force feedback (f_{max}, C_{max}) and the size of the task workspace (R_E, θ_E), where R_E denotes the radius of the smallest sphere which encloses the translational workspace and θ_E is the maximal angle accessible in all directions in the rotational workspace. Then, the acceptable level of drift K_{drift}, defined as the percentage of drift force over the force feedback and the device velocity, is tuned by the user to adjust his/her preferred perception of the task interactions.

[0020] To simplify the mathematical definition of the workspace dynamic mapping in the following, the terms are written separately for the rotational and translational motions/forces. The haptic device velocity, imposed by the human, is expressed by $\dot{X}_d=[v_d\ \omega_d]^T$. The haptic device position X_d is divided into the Cartesian position r_d and a rotation angle θ_d around the unit vector s. Similarly, the center of the haptic device workspace is defined though r_{d0} and θ_{d0} around the directional vector s_0. The controlled robot position X_r can be defined in the same way by the Cartesian position r_r and a rotation angle θ_r around s_r. The drift velocity is $\dot{X}_{drift}=[v_{drift}\ \omega_{drift}]^T$ and the associated drift force $F_{drift}=[f_{drift}\ C_{drift}]^T$. The center X_w of the task workspace moves to the Cartesian position r_w and is rotated by an angle θ_w around the unit vector s_{drift} with respect to the haptic device drift. The rotation matrix $R\_=\mathrm{Rot}(\theta\_, s\_)$ describes the frame rotation of an angle $\theta\_$ around the vector $s\_$.

Overall Adaptive Workspace Mapping Controller

[0021] The adaptive workspace mapping controller merges a continuous indexation of the haptic device to its home position, re-centering the task workspace to the area of interest without being perceived by the user, with an adaptation of the scaling factor with respect to the distance to the device workspace boundary. The overall controller bloc diagram is shown in FIG. **4** and describes the framework of the mapping algorithm in haptic teleoperation.

[0022] The human operator commands the robot position X_r by moving the haptic device within its workspace. The haptic device position X_d has to be properly mapped into the robot workspace to keep the accuracy of the remote motion while being able to reach any area of the task environment.

[0023] Performing a fine task in a large environment is a challenging problem in teleoperation due to the physical limitations of the haptic device. This problem is addressed in this invention by continuously adapting the scaling factor K_s in motion and force between the haptic device and the controlled robot. The scaling factor is increased to reach the boundary of the task environment with coarse motions, while it decreases to offer a good accuracy to the user when achieving fine tasks.

[0024] However, a high-performance mapping algorithm must offer the same precision in fine motions—by applying a small scaling factor—in any areas of the environment. This requires to relocate online the center of the task workspace to the area of interests, and drift relatively the haptic device back to its center. This indexation of the haptic device must be smooth enough to stay imperceptible by the user and stiff enough to quickly slide the task workspace and lower the scaling factor to an accurate ratio. The drift computation is the second key component of the workspace mapping controller.

Drift of the Workspaces

[0025] The drift controller manages the progressive relocation of the haptic device back to its workspace center during the remote task. This drift-based strategy is based on the observations that human beings are significantly influenced by their visual observation and have a rough estimation of their hand location in space. Considering these observations, soft and small deviations of the haptic device toward its center will not be perceived by the user as long as the controlled robot keeps following the requested trajectory without reproducing the drift. This principle allows to index the haptic interface online without disturbing the user perception nor affecting the remote task performances.

[0026] An initial mathematical definition, from U.S. Pat. No. 7,626,571, computes the drift translational velocity as the product of the haptic device instant velocity and the offset position of the device with respect to its center:

$$v_{drift} = -\frac{K_d}{R_{max}}|v_d|(r_d - r_{d0}).$$

In this expression, K_d is a drift factor and represents the percentage of drift velocity over the device instant velocity. It gives the maximum level of deviation which can occur to shift the device back to its center.

[0027] With this formulation, the drift only occurs during motion of the user hand and even stays proportional to the user velocity to limit the spatial distortion between the physical—haptic device displacement—and visual perceptions—visual display or direct observation of the robot. However, it sets a drift velocity to the haptic device regardless the interaction forces with the environment. Therefore, the drift can create forces inconsistent with the task interactions, and eventually disturb the user perception. On the other hand, such a velocity-based drift would be close to zero during in-contact quasi-static tasks, although the feedback of the interaction forces could make a strong drift imperceptible to the user. The new drift algorithm improves the task performances by adding a drift force component in the direction of the interaction force F_{task} with the environment. The total drift force is then computed as $F_{drift}=K_p \dot{X}_{drift}\ K_{df}\ F_{task}$. K_p is the impedance gain that generates a force from the drift velocity. K_{df} gives the percentage of drift force over the force feedback and is, together with K_d, the only input parameter to tune according to the user preferences. Thanks to this new formulation, the drift controller is consistent with the haptic feedback from the task and becomes powerful in contact tasks The addition of the drift force and the task force constitutes the haptic feedback $F_{hapt}=(F_{drift}+F_{task})/K_s$, which is inversely scaled to be consistent with the device motion. Before being transmitted to the user, the haptic feedback is saturated at the maximum force capabilities of the device (f_{max}, C_{max}). With this control strategy, the haptic feedback conveys the sense of the task interaction, while imperceptibly drifting the hand of the user back to the center of the haptic device workspace.

[0028] The presented drift strategy is extended to rotational motions to be suitable for 6-DOF haptic device and any applications. The drift rotational velocity becomes

$$\omega_{drift} = -\frac{K_{dR}}{\theta_{max}}|\omega_d|\theta_d s.$$

In this expression, and in the following, θ_d represents the rotation angle around s relatively to the initial orientation (θ_{d0}, s_0) of the haptic device.

[0029] When the haptic device is continuously indexed, the remote motion of the robot must follow the user input motion to accurately perform the task. The position of the controlled robot X_r is then computed by considering both the haptic device set position X_d and the drift command F_{drift}. By neglecting the effective inertia of the haptic device plus human hand, which is hard to estimate without complex modeling, the actual drift displacement of the haptic device can be reasonably approximated by $\hat{X}_{drift}=dt^2\ F_{drift}=[\hat{r}_{drift}, \hat{\alpha}_{drift}]^T$. This drift displacement induces an opposite sliding of the task workspace center expressed by $r_w(t)=r_w(t-dt)-K_s \hat{r}_{drift}$ and a rotation of the task frame described by the rotation matrix

$$R_w(t) = R_w(t-dt)\times Rot(\theta_w, s_{drift}) \text{ with}$$

$$\theta_w = -K_{sR}\|\hat{\alpha}_{drift}\| \text{ and } s_{drift} = \frac{\hat{\alpha}_{drift}}{\|\hat{\alpha}_{drift}\|}.$$

[0030] Finally, the robot command position at time t combines the human input and the drift as follows: $r_r(t)=r_w(t)+K_s(r_d(t)-r_{d0})$ and $R_r(t)=R_w(t)\times Rot(K_{sR}\times\theta_d(t),s(t))$

Ranging the Scaling Factor

[0031] As shown in the expressions of the robot position and orientation, the remote motion is multiplied by the scaling factors K_s in translation and K_{sR} in rotation. The inverse scaling factors are applied to the force feedback to be consistent with the motion scaling.

[0032] To make the mapping controller suitable to various applications, a technical contribution of the present invention is to adapt the scaling factors, online, with respect to the task required accuracy and the device and environment workspace size. The ranging of the scaling factor can be done in different ways. Its objective is to adjust the precision of the remote force and motion to be consistent with the task demand while preventing the user to reach the boundary of the haptic device workspace.

[0033] In an exemplary implementation, it is chosen to vary the scaling factors linearly according to the distance to the haptic device workspace boundaries. When moving the device close to its center, the scaling factor is set to 1 to give a high precision to the user in the remote actions. When the user imposes large or free-space motions to the device and quickly approaches the device workspace limits, the scaling factors are increased to extend the reachable area in the robot environment. Therefore, the scaling factors are expressed by:

$$K_s = 1 + \frac{\|r_d - r_{d0}\|}{R_{max}}\left(\frac{R_E}{R_{max}} - 1\right) \text{ and } K_{sR} = 1 + \frac{\theta_d}{\theta_{max}}\left(\frac{\theta_E}{\theta_{max}} - 1\right).$$

[0034] This adaptation of the scaling factors offers a nice balance between the task accuracy and the haptic device mechanical limitations. It is also designed to complement the effect of the drift controller when not sufficient enough to offset the hardware limits. Indeed, in coarse or free-space motions the drift is too light to index the haptic device back to its center. The increase of the scaling factors is required to prevent the user to reach the device workspace limits while exploring the entire environment. When achieving fine tasks in a small zone of the environment, the drift relocates the task workspace to the area of interests. Decreasing the scaling factors to 1, or even lower, provides the user with a good force/motion accuracy to perform and perceive fine remote tasks.

What is claimed is:

1. A drift-based adaptive workspace mapping controller for haptic applications, comprising:

(a) a robot controller;

(b) a haptic device controller; and

(c) a haptic-robot interaction controller having a control strategy, wherein the control strategy combines a drift-based approach and an adaptive scaling to map exchanged force and motion data from one robot space to a haptic device space, and

wherein the haptic-robot interaction controller has hardware and task input parameters, defined as a haptic device workspace size, a maximum force feedback, a size of the task workspace, and user preferences, given through a percentage of acceptable drift force over a force feedback and a percentage of acceptable drift velocity over the device instantaneous velocity, which adjust a workspace mapping to a teleoperation system.

2. A control method of workspace mapping for haptic-robot or haptic-avatar interactions, comprising:

(a) having a robot or a virtual avatar of the robot;

(b) having a haptic device; and

(c) controlling haptic-robot interactions or haptic-avatar interactions, wherein the control includes calculating and applying an adaptive scaling factor to exchanged forces and motions in the haptic-robot interactions or the haptic-avatar interactions, wherein the adaptive scaling factor is based on a task accuracy and an environment size in which the task is performed; and

(d) computing and applying a drift force to move the haptic device at its workspace center and to relatively move the robot to the task area of interest, wherein the drift factor is based on a haptic device velocity and a task interaction force.

* * * * *