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(54) **ADVANCED MECHANICAL LEARNING SYSTEM**

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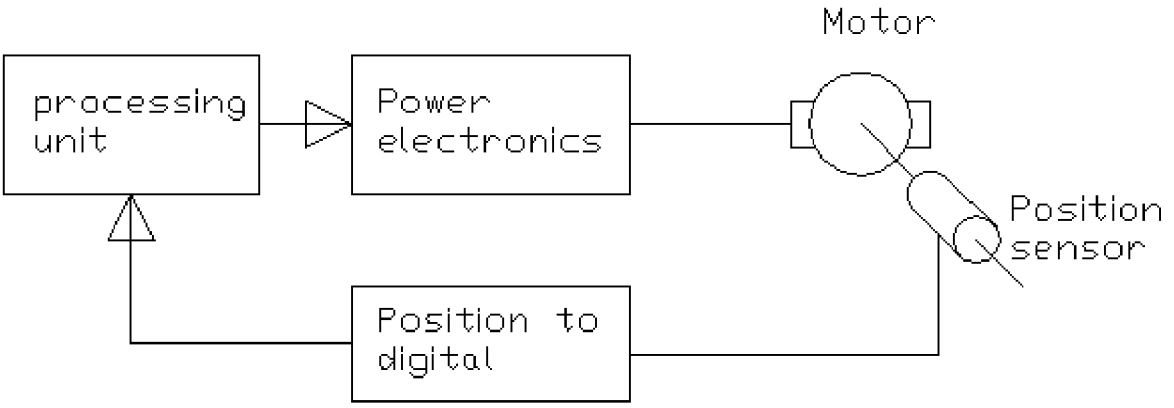
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(57) **ABSTRACT**

The subject of this invention is a novel mechanical learning system. The system proposed in this invention provides a method to speed up and control the learning process of an arbitrary mechanical movement with arbitrary mechanical loading and specified complexity and accuracy.



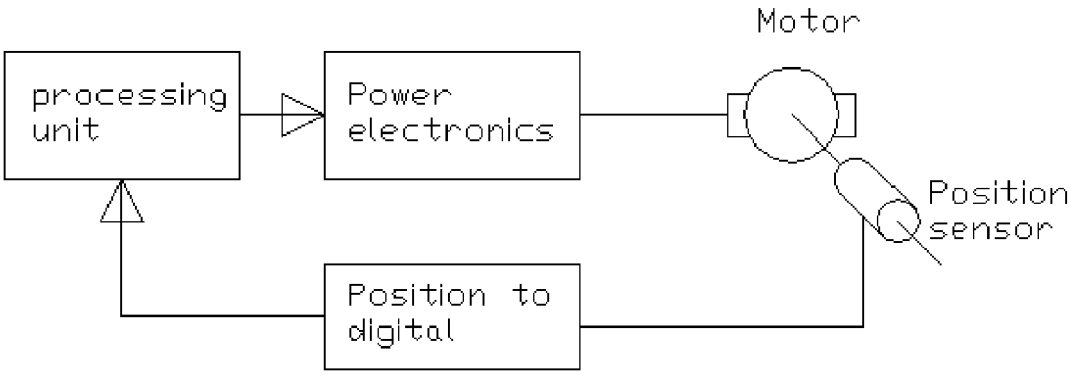

Motor
processing unit
Power electronics
Position sensor
Position to digital

Fig. 1

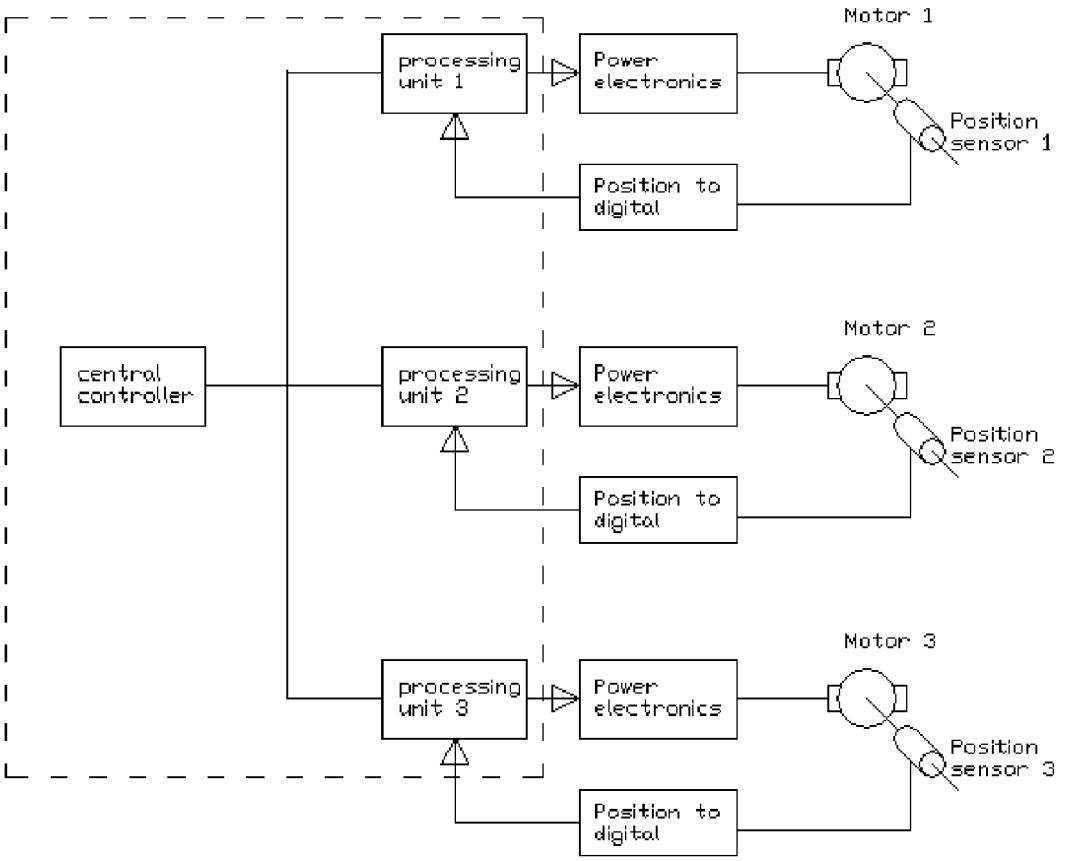

central controller
processing unit 1
processing unit 2
processing unit 3
Power electronics
Power electronics
Power electronics
Position to digital
Position to digital
Position to digital
Motor 1
Motor 2
Motor 3
Position sensor 1
Position sensor 2
Position sensor 3

Fig. 2

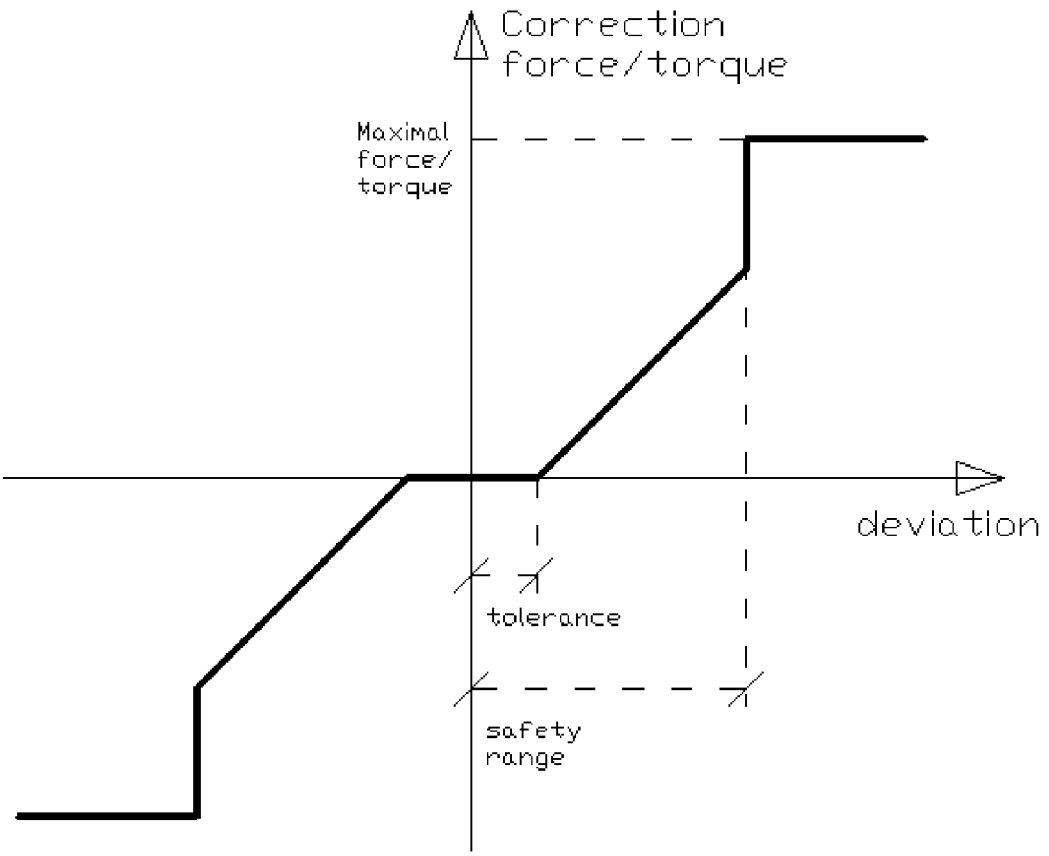

Correction
force/torque
Maximal
force/
torque
deviation
tolerance
safety
range

Fig. 3

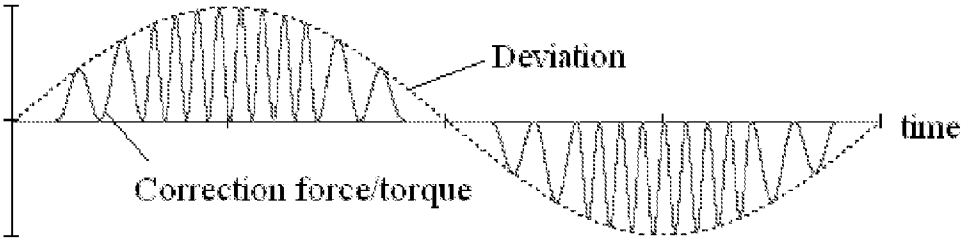

Deviation
time
Correction force/torque

Fig. 4

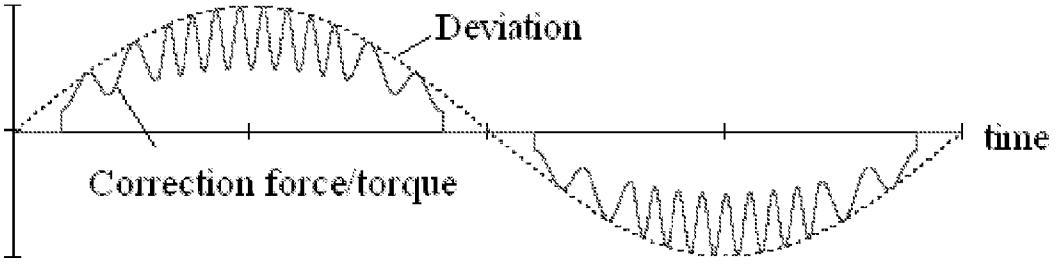

Deviation
time
Correction force/torque

Fig. 5

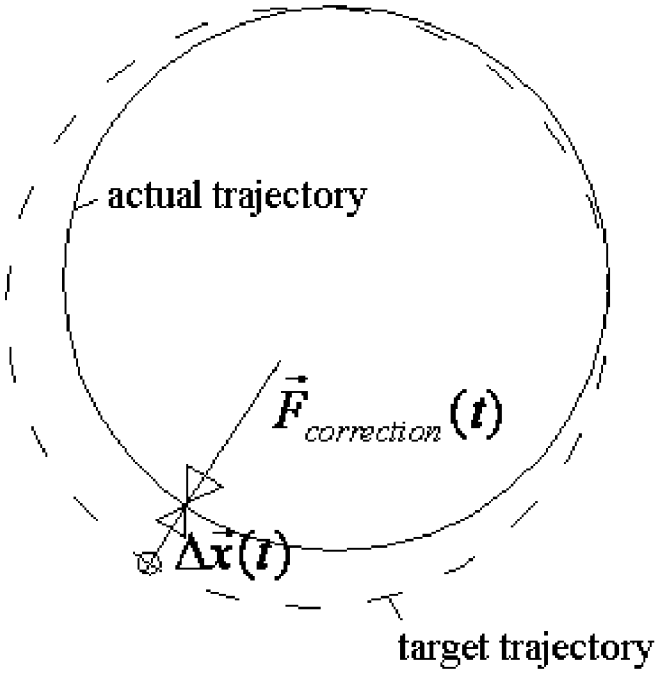

actual trajectory
$\vec{F}_{correction}(t)$
$\Delta\vec{x}(t)$
target trajectory

Fig. 6

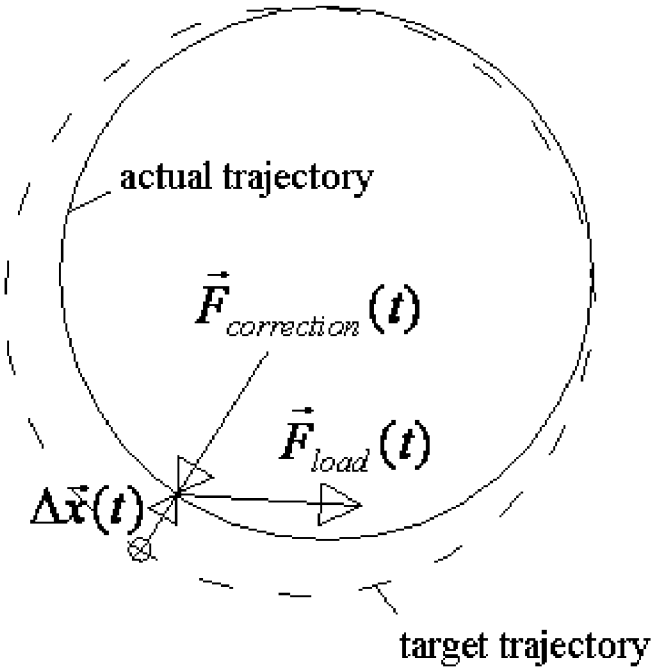

actual trajectory
$\vec{F}_{correction}(t)$
$\vec{F}_{load}(t)$
$\Delta\vec{x}(t)$
target trajectory

Fig. 7

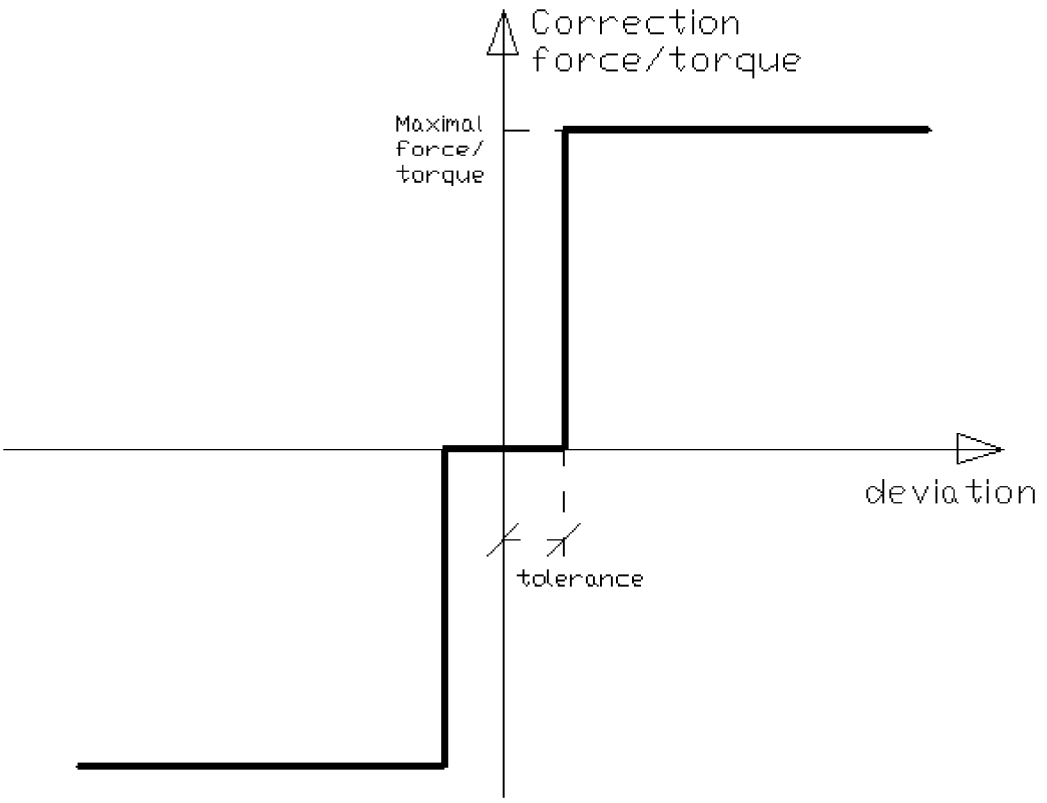

Correction
force/torque
Maximal
force/
torque
deviation
tolerance

Fig. 8

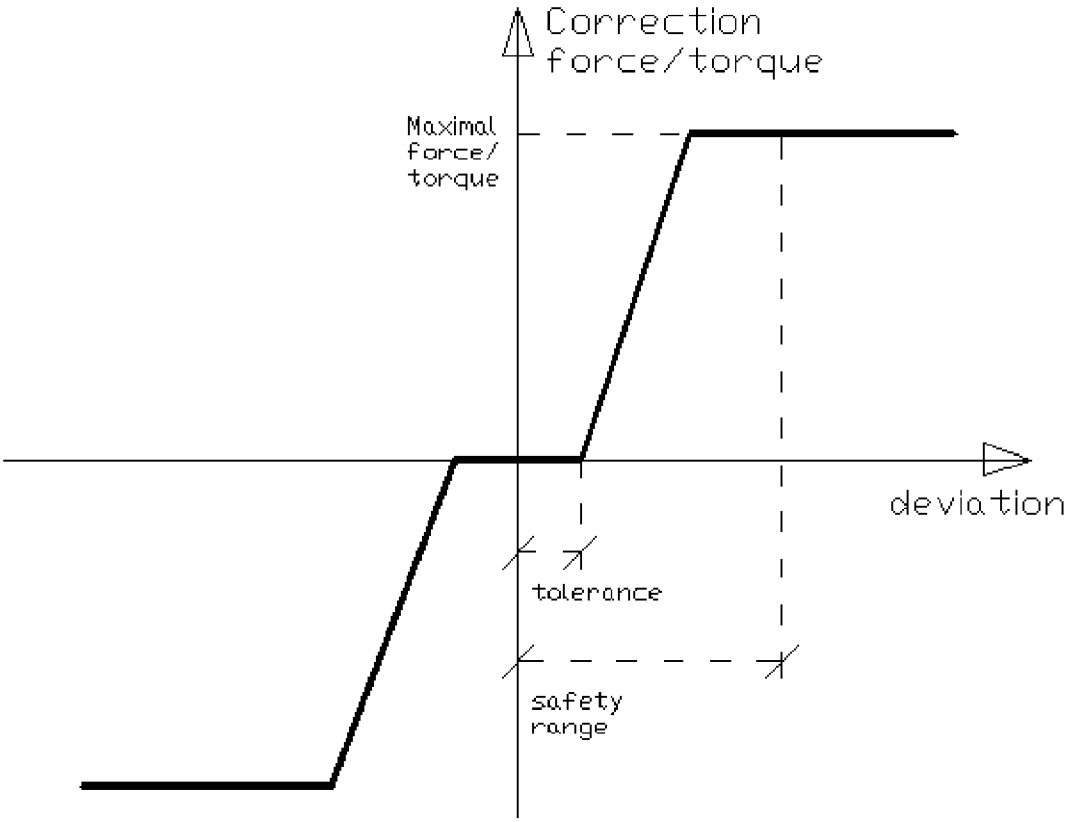

Correction
force/torque
Maximal
force/
torque
deviation
tolerance
safety
range

Fig. 9

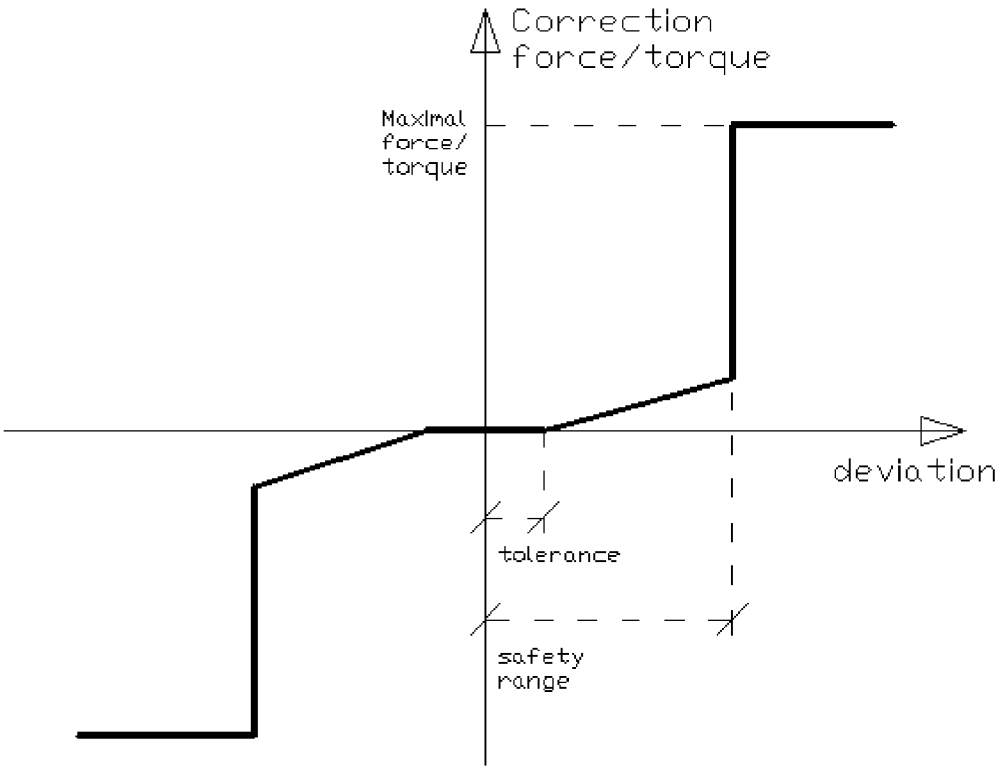

Correction
force/torque
Maximal
force/
torque
deviation
tolerance
safety
range

Fig. 10

ADVANCED MECHANICAL LEARNING SYSTEM

FIELD OF INVENTION

[0001] The present invention relates to a learning process through a mechanical system of an arbitrary movement with an arbitrary mechanical loading being present. It can be relevant to sport activity, art or for rehabilitation purposes.

DEFINITIONS

[0002] Stiff system: large forces are generated when small deviations are present

[0003] Compliant system: moderate forces are produced at moderate deviations

[0004] Very compliant system: large deviations result in small force differences

[0005] Absolutely compliant system: large deviations do not cause any force differences

[0006] Loading: a system of forces and torques that simulates an object, tool, weight, sports object or any arbitrary action that might be enforced upon the user in the real situation.

[0007] Position: an instantaneous value of a considered function, such as a position of an actuator, angular or translational position of a mechanical system, position in space, or the first or the second derivatives of this function

[0008] Trajectory: a sequence of positions either associated with a fixed or a variable time interval. It is assumed that these positions produce a closed loop.

BACKGROUND

[0009] By now there is enough evidence published in the literature that various movement parameters are encoded by neurons in the motor cortex. Recent results suggest a monotonic or linear encoding. This means that the trainee is gradually gaining a certain mechanical memory and whether this memory is right or wrong should be constantly verified during the very process of learning. Because of monotonic character of the learning process, changes on the earlier stages would have been much more effective compared to the later intervention. Besides, the user has to have a possibility to adjust himself to the actual loading conditions. So the system has to provide the realistic loading pattern. Eventually the learning process would be complete if the user is capable of repeating the required trajectory with a specified accuracy and with the realistic force pattern being applied.

[0010] A number of partial solutions of this problem have been presented in earlier patents devoted to various learning systems.

[0011] In the patent U.S. Pat. No. 5,879,269 a training device is proposed with a possibility to provide a variable force. The system described in this patent is dealing with a one-dimensional rotational motion and there is no direct control of angular displacement. A rotation speed is used instead. Since the system described there is limited to the one-dimensional case, nothing is spoken of a complex trajectory and no control means are suggested for maintaining this trajectory.

[0012] In the patent U.S. Pat. No. 6,899,656 a system is proposed for generating an arbitrary 2D force pattern. However in this system a clear emphasis is made on generating the force pattern rather than on providing a specific displacement. Nothing is spoken of a correcting action, which means that this system is also insufficient for learning a mechanical movement.

[0013] The system described in the patent U.S. Pat. No. 6,666,831 is based on two two-dimensional actuating systems having an incorporated feedback mechanism in it. However nothing is mentioned on how this feedback is actually realized. The system described in U.S. Pat. No. 6,666,831 is aimed at rehabilitation and is limited to the stepping motion. Besides, it does not provide a method for specifically loading the patient. The system uses actuators for auxiliary or assisting purpose. For the rehabilitation purpose this solution might be enough. However in order to simulate an action of handling a weight, a tool, a sport object or some arbitrary action a force or torque system would be required. This force or torque system is further referred as external loading or just loading. The absence of an external loading makes this approach insufficient for a general case, because as recent investigations reveal, some extra adaptation of the user is needed if the force pattern is changed.

[0014] In the patent U.S. Pat. No. 7,066,896 there is a description of a complex system provided for rehabilitation purposes. This system provides complex movements and these movements are applied in a cyclic manner. But the user cannot change the path of a prescribed movement. So the movement is enforced upon the user. Lack of room for a free movement deprives the user from practice, which makes such learning incomplete. Practically anyone going once and a while into the gym can tell that there is quite a difference between a free and a restricted motion. If an individual is regularly using a facility with a rigidly restricted trajectory and then he switches to the facility where this restriction is less pronounced, he would most certainly notice considerable deviations from the original trajectory, which is a clear indication that he was used to the rigid restriction.

[0015] Thus there is no system or method available for a complete learning process of an arbitrary trajectory with an arbitrary loading pattern. Such a method and corresponding system are proposed in this invention.

SUMMARY OF THE INVENTION

[0016] The system described in this invention is based on a control of a specified number of degrees of freedom with an actuating and a monitoring system established for each degree of freedom. The monitoring system is used to guide the user's movement and calculate the deviation from the target movement. The actuating system is used for two purposes, namely for applying the mechanical load, being a part of the training, and for providing a correcting force. Since the user might have a difficulty of distinguishing the correcting force from the actual load, the system is capable of applying the correcting force in a pulsating mode.

[0017] The system is completely parameterized and permits a certain tolerance. This means that a certain minor deviation from the specified trajectory can be neglected if the user wishes so. There is a possibility included for a gradual modification of this tolerance upon evaluation of the user's performance. Besides, the tolerance can be explicitly set for any part of the trajectory.

[0018] By producing the correcting action the system defines a flexible restriction for the deviation from the target trajectory. There is a safety range introduced for each degree of freedom, which can be altered for each part of the target trajectory. The degrees of freedom may be the degrees of

freedom of actuators themselves or a set of degrees of freedom after a certain coordinate transformation (Cartesian, cylindrical, spherical, Denavit Hartemberg or other types).

[0019] There is a possibility for choosing a priority of learning—either it would be a trajectory or the loading. In case if the trajectory is given the highest priority, the loading can be somewhat modified upon the analysis of the learning process. Different other measures are foreseen. In case if the loading is given the first priority, then the applied loading remains constant and the correcting action is applied in a pulsating mode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] The features and advantages of the proposed system are clarified in the following figures:

[0021] FIG. **1** shows the principle control circuit for a module controlling a single degree of freedom.

[0022] FIG. **2** shows a general view of the learning system controlling 3 degrees of freedom.

[0023] FIG. **3** shows a general variation of the correction force as a function of the deviation from the target trajectory. It is a combination of stiff, compliant and absolutely compliant areas.

[0024] FIG. **4** shows an example of pulsating correction force. The deviation and the force are shown in relative units, that is the maximum absolute value of the displacement concurs with the maximum absolute value of the force on the graph. This is done for illustrating purpose.

[0025] FIG. **5** shows an example of pulsating correction force with an offset. The deviation and the force are shown in relative units, that is the maximum absolute value of the displacement concurs with the maximum absolute value of the force on the graph.

[0026] FIG. **6** shows an example of dependence between the deviation from the target trajectory and correcting force in a 2D case.

[0027] FIG. **7** shows an example of dependence between the deviation from the target trajectory and correcting force in a 2D case with a loading present.

[0028] FIG. **8** shows a dependence of the correction force on the deviation with an absolutely rigid restriction of the permitted deviation.

[0029] FIG. **9** shows a dependence of the correction force on the deviation with a medium rigid restriction of the permitted deviation.

[0030] FIG. **10** shows a dependence of the correction force on the deviation with a soft restriction of the permitted deviation.

DETAILED DESCRIPTION

[0031] It is common in mechanics to decompose any movement of an object into a number of independent vector quantities called degrees of freedom. An elementary mechanical movement constitutes either translation or rotation. Two movements with equivalent decompositions are also equivalent. So in order to achieve equivalence of two movements it is sufficient to achieve equivalence of translational displacements or angular rotations along each of the degrees of freedom used for decomposition of these movements. For the sake of simplicity, let us focus on a single degree of freedom. The user is performing a certain periodic movement x(t). This movement can and most certainly will deviate in the beginning from the desired movement X(t) both in time and value. There is a correcting force needed acting in the direction opposite to the deviation.

[0032] The correcting force is created by the actuating unit of the module shown in FIG. **1**. The same module carries out monitoring of the considered degree of freedom. This is an additional novelty of the system, that all the functionality required for operating a single degree of freedom is incorporated into a single module.

[0033] Monitoring the trajectory and calculating the deviation along with the correcting action is performed in the processing unit (see FIG. **1**). The power electronics is an intermediate unit, necessary for transforming the control signal from the processing unit in order to operate the motor. Either an electric or hydraulic or pneumatic actuators or motors can serve as the "motor" indicated in FIG. **1**.

[0034] In general case the module contains an independent mechanical system for an attachment to the user, for monitoring the required degree of freedom and for providing the correction force and the load.

[0035] A general view of the learning system controlling 3 degrees of freedom is shown in FIG. **2**. Generally, the learning system consists of a multitude of modules and a central controller. The modules can have actuators, position sensors and power electronics units of different types and accordingly programmed processing units. The central controller is responsible for coordinating the operation of the modules.

[0036] Since mechanical systems of the modules of the learning system are generally independent, the existing models can be decoupled, replaced or additional modules can be attached to the learning system.

[0037] For economical reasons, two or more modules can be combined into a fixed element. Such a fixed element has a single mechanical system. Yet each degree of freedom within these elements is controlled as described above.

[0038] A general variation of the correction force as a function of the deviation from the target mechanical function is presented in FIG. **3**. There are three main areas in this dependence. The first area is restricted by the specified tolerance. This area does not have to be symmetric with respect to the origin. If the user's deviation remains within specified tolerances, then no correcting action is produced. The second domain is the domain of dependence between the correcting action and the deviation. This dependence does not have to be linear. In general, the relation between the correcting action and the deviation in the second domain has to be defined by a polynomial. Again, this relation does not have to be the same for the first and for the third quadrant of the graph. The second domain must remain within the safety range, which does not have to be symmetric with respect to the origin. The safety range is determined with a purpose of not to inflict any damage to the user and to the equipment during training. If for some reason the user approaches the boundary of the safety range he would feel a considerable increase of the correcting force. The maximal force is the value that should not be reached, so that the user would be unable to hurt himself. The actuator of each module and the power supply of the actuator must be chosen accordingly. If the user wishes to train with the loading force being present, the correcting action in the second domain, described above, will be switched to the pulsating mode, as shown in FIG. **4**. In general case not only the amplitude of the action pulses, but also the frequency of the pulses should be adjusted in accordance with the mea-

sured deviation. The correcting force can also be provided with an offset as shown in FIG. **5**.

[0039] An example of dependence between the deviation and correcting force for a 2D case is shown in FIG. **6**. Notice that here the deviation and correcting force are depicted as vector quantities. The correcting force in this case can either be a monotonous or a pulsating function of the displacement upon the user's preference.

[0040] In the presence of an arbitrary load as shown in FIG. **7** the correcting force will generally have a pulsating shape with or without an offset. The user will feel directional pulsations of variable frequency, which would at least inform him of the required corrections and guide or push him depending on the actual amplitude of the force towards the target trajectory.

[0041] If the deviation becomes excessive and the user reaches the boundary of the safety range for any of the degrees of freedom, then the learning system switches from the pulsating mode to the monotonous correction mode. This can be done either for all the modules, for a group or modules or for a single module. The load would be gradually reduced if trajectory is given the highest priority. With respect to the load force, it could also be provided by means of devices external to the learning system, such as, for instance, weights or elastic elements. The system will use then the pulsating correcting action while operating within the safety range. The learning system must be informed about the additional inertia and location of this inertia in order to adjust the correcting action accordingly. Upon reaching the boundary of the safety range the system will switch from the pulsating mode to the monotonous correcting force. This again can be done either for all the modules or just for a group or modules.

[0042] This is necessary if the user gets an injury or feels any discomfort during training. The user would be able to give up training at any point of the trajectory and the learning system would prevent him from damaging himself.

[0043] The learning process can be determined as follows:

A. Preparation of the Learning System:

[0044] 1. Definition of the trajectory. The trajectory can either be downloaded from a computer or recorded, that is a trainer can switch the learning system into the monitoring mode and let the system record the intermediate positions while he is performing the exercise. The whole recorded motion or any part of it can be rescaled in time.

[0045] 2. Adjusting the trajectory for the specific user if necessary.

[0046] 3. Defining the initial tolerances, the target tolerances and the safety range as a function of position and/or time for each degree of freedom.

[0047] 4. If external loads are used, the parameters of these loads must be specified.

[0048] 5. The user can define the priority of learning, i.e. either the trajectory should be respected or the mechanical load.

B. Operation of the Learning System:

[0049] 1. The user has to get a feeling of the trajectory. Therefore the system generates the monotonous correcting action in accordance with the dependence shown in FIG. **8**. This mode corresponds to the rigid restriction of deviations from the target trajectory. Initial, normally larger, tolerances are used by the system.

[0050] 2. The load will gradually build up and the system will gradually reduce the rigidity of the restrictions as shown in FIG. **9**, while the training goes on.

[0051] The user performs the specified exercise in a cyclic manner. If the load is present, the system uses a pulsating correcting action. Otherwise the correcting action is monotonous. The decision on whether the learning system should reduce the restrictions comes from the central controller after evaluating the total deviation. The restrictions can be softened either for the whole learning system or just for a specific limb or for a certain degree of freedom.

[0052] 3. As the user is improving his performance and correcting actions reduce in their amplitude, the restrictions will soften to the dependence shown in FIG. **3** and further to the dependence shown in FIG. **10**.

[0053] 4. The tolerance gradually reduces.

[0054] 5. If the user's performance worsens, the system will increase the rigidity of the restrictions accordingly in order not to let the user to learn a mistaken movement. If the target trajectory is given higher priority compared to the load then the load can be temporarily reduced. If the user improves his performance, the load can be gradually restored.

[0055] 6. If the user is capable of performing the target movement with a sufficient repeatability, that is while remaining within the final tolerance with the required load being present, and without any correcting action being used, then the exercise is complete.

C. Analysis of the Data.

[0056] The decisions made by the central controller are based on the general user's performance and not just on the user's performance during the last cycle.

[0057] The corresponding data is either recorded into the central controller or stored in the processing units within each module. The acquired history of the user's performance can be used for a further optimization of the learning programs.

[0058] A figure of merit can be given to the trainee, depending on some statistics of deviation, such as mean deviation magnitude, root mean square, peak.

The system offers numerous advantages and unique features, such as:

[0059] 1. A segmentation technique is proposed allowing parallel control of numerous degrees of freedom and providing complex mechanical load. This means that the load can be as complex and multidimensional as the target trajectory. So far these two features have never been brought into the single learning system.

[0060] 2. There is a novel two-way adaptation approach implemented in the proposed learning system, namely while the user is adopting to the required trajectory and the load pattern, the learning system is adopting the learning program in accordance with the user's performance.

[0061] 3. The central controller can modify the restrictions for a certain group of modules. This way an individual approach is used not only for each new user, but also his limbs can enjoy an individual approach.

[0062] 4. There is a novel mechanical recognition approach implemented in the system in order to let the user to distinguish between the two forces. This is implemented by using a pulsating correcting action with varying amplitude and varying frequency.

[0063] 5. There is a novel flexible safety system incorporated into the learning system, since the safety ranges described earlier can be determined for each degree of freedom and for each time step of the target function. This approach is superior to establishing operational limits using mechanical means. Besides, the user is provided with a possibility to safely abandon the exercise even before leaving the learning system. If the boundary of the safety range is repeatedly reached, the system will stop the training and produce a signal in order to attract attention. So even if the user is unconscious, he would be secured from any damage.

[0064] 6. There is a recording option provided for defining the exercise. This will considerably speed up making the new learning programs for complex movements. The recorded motion can be scaled in time in order to facilitate adaptation of the trainees. Scaling in time is also introduced as an option in the control program in the processing unit.

[0065] 7. Since the tolerances for each degree of freedom can be defined for each point of the trajectory, there is a possibility for focusing on a specific part of the trajectory.

[0066] As those skilled in the art can modify the layout and the method of the disclosed learning system, we intend that the claims be interpreted to cover such modifications and equivalents.

What is claimed is:

1. A learning system comprising a central controller and a multitude of modules either mechanically connected to the user or having mechanical contact with the user and controlling individual degrees of freedom.

2. A module of the learning system controlling a single degree of freedom comprising:

a. the mechanical system with a position sensor aimed for monitoring the movement along this degree of freedom and an actuator for producing a correcting force or a torque along this degree of freedom and mechanical load along this degree of freedom;

b. the processing unit with predefined information about the target trajectory, acquiring information on position from the position sensor and controlling the actuator through the power electronic unit.

3. The module of the learning system as described in claim **2** with a processing unit comprising a control program for generating either monotonous or pulsating correction force or torque or a combination of both in function of the deviation from the target trajectory with a possibility for modifying the frequency and the offset of the pulsating force or torque in function of the deviation from the target trajectory.

4. The module of the learning system as described in claim **3** with a processing unit comprising a control program with predefined information on the acceptable deviation from the target trajectory for each point of the target trajectory.

5. The module of the learning system as described in claim **3** with a processing unit comprising a control program with predefined information on the safety limits for each point of the target trajectory. The program comprises any combination of the following items:

a. Upon reaching these limits the module generates the maximal correction force;

b. The mechanical load generated by the module is reduced to zero.

6. The module of the learning system as described in claim **3** with a processing unit comprising a control program permitting resealing in time of either a portion of the target trajectory or the whole target trajectory and allowing according resealing in time of the mechanical load.

7. The module of the learning system as described in claim **3** with a processing unit comprising a control program allowing for recording the user's motion with a further use of this motion as a target trajectory during training.

8. The group of modules of the learning system as defined in claim **2** sharing the same mechanical system.

9. A central controller of the learning system comprising:

a. at least a control program used for synchronization of the operation of individual modules;

b. at least a control program used for producing a monotonous or pulsating correcting action by a group of modules if the user deviates from the target trajectory beyond the acceptable tolerance;

c. at least a control program used for producing a monotonous correcting action by a certain group of modules or all the modules in case if the user is reaching the boundary of the safety range;

d. at least a control program used for producing the maximal monotonous correcting action by a certain group of modules or all the modules in case if the user is reaching the boundary of the safety range;

e. at least a control program used for reducing the mechanical load to zero if the user is reaching the boundary of the safety range;

f. at least a control program used for modifying the acceptable deviation from the target trajectory;

g. at least a control program used for modifying the relation between the correcting actions of the group of modules of the learning system;

h. at least a control program used for recording the movement of the group of modules of the learning system with a further use of this movement as a target trajectory during training;

i. at least a control program used for rescaling in time of the part of the target movement or the whole movement of the learning system with according rescaling of the mechanical load;

j. at least a control program used for registering an external load or external weights used by the user in order to switch to the pulsating correcting mode when necessary and take into account the additional inertia;

k. at least a control program used for external input of a target trajectory and variation of the mechanical load for each module of the learning system;

l. at least a control program used for recording the user's performance and providing an output of the user data.

* * * * *