



Article Improving the Force Display of Haptic Device Based on Gravity Compensation for Surgical Robotics

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Abstract: Haptic devices are applied as masters to provide force displays for telemedicinal robots. Gravity compensation has been proven to be crucial for the accuracy and capability of force displays, which are critical for haptic devices to assist operators. Therefore, the existing method suffers from an unsatisfactory effect, a complex implementation, and low efficiency. In this paper, an approach combining active and passive gravity compensation is proposed to improve the performance of a force display. The passive compensation is conducted by counterweights fixed with the moving platform and pantographs to offset most of the gravity and reduce the loads of the motors, while the peak capability of the force display is enhanced. The required weight is optimized by a multi-objective genetic algorithm in terms of the maximum torque of the motors in the global workspace. As a supplement, the residual gravity is eliminated by active compensation to extend the accuracy of the force display. The balancing forces in the discretized workspace are entirely calibrated, and the required force for the arbitrary configuration is calculated by interpolations. The decisions regarding the algorithm parameters are also discussed to achieve a compromise between the effect and elapsed time. Finally, the prototype with a compensation mechanism is implemented and experiments are carried out to verify the performance of the proposed method. The results show that the peak capability of the force display is enhanced by 45.43% and the maximum deviation is lowered to 0.6 N.

Keywords: telemedicine robot; haptic device; gravity compensation; parallel mechanism

1. Introduction

In recent years, a variety of surgical robots have been developed to assist surgeons in performing operations [1–4]. In typical surgical robots with teleoperations such as Da Vinci for minimally invasive surgery and NeuroArm for neurosurgery, the surgeons are allowed to remotely complete surgery in a comfortable and safe environment, while the haptic device is applied as a master to capture the operation intention of the surgeon and filter out the hand tremors [5,6]. The force signals taking place in the slave effector are fed back to the operator via haptic devices, which have proven to be beneficial to mission efficiency and surgical security [7]. An accurate and sufficient display force is important for the desired transparency of teleoperations, while it also provides active constraints to avoid vital nerves or arteries [8,9]. Meanwhile, the size and power of the adopted actuators in haptic devices are strictly limited for a lower inertia and higher bandwidth. In this case, the weights of the components are critical to the capability of the force display and gravity compensation is essential to improve the performance of haptic devices for teleoperations [10].

In existing devices, the gravitational forces are compensated by passive or active methods. Passive compensation is conducted by energy storage elements to reduce the potential energy fluctuations, which requires no extra energy consumption and enhances the capability of the force display [11]. The required torques caused by the gravity of the components are performed by actuators in active compensation, while the adverse impact on the accuracy of the force display is eliminated. Various solutions have been devised for



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). series mechanisms, but they are still unsatisfactory in terms of complexity and usability, especially for parallel mechanisms with closed-chain properties.

Springs and counterweights are common elements of passive compensation, which are fixed on the chains in conventional approaches [12–14]. A novel mechanism was proposed as a haptic device, and counterweights were employed to reduce gravitational torques of joints [12]. The full gravity compensation was also realized by counterweights for a parallel mechanism with six DOFs in [13]. Although the compensation with counterweights on chains is efficient, it suffers from a distinctly increased mass and weakened dynamical properties. Moreover, the required weights may be several times heavier than the original components due to the finite transmission efficiency between the chain and the end platform, which is detrimental for haptic devices. The components' own weights are used as a feasible method, which requires a reasonable design and detailed calculation [14]. On the contrary, lightweight springs are also widely used for gravity compensation. The compensation of the planar mechanisms was introduced and derived in [15]. A haptic device with gravity compensation by extension springs is proposed in [16]. The static balance of a parallel mechanism with a constant-orientation platform was achieved by elastic systems with the zero-free-length (ZFL) property in [17]. An approach with a full compensation for Delta was presented, and a simplified solution with an acceptable effect is finally recommended in [18]. Modified designs with moderate elastic systems are also used on the joints to provide approximate compensation [19]. In spite of the proper effect and light weights, additional mechanisms are adopted, and extra modification is required by the involved elastic systems for the ZFL property, which increase the difficulty of implementation [20]. The constant force applied on the end platform is adopted as a feasible design for the compensation of the parallel mechanism [21–23]. It provides considerable effects and convenient implementation, without compromising the kinematic performance of the original mechanism.

The residual gravity is eliminated by joint actuators for active compensation, which is employed as a complementary method. This combined strategy is adopted by a haptic device with the Delta architecture, while the performance of the force display is enhanced [24]. The gravity compensation of the 3-RPS parallel machine is realized by three adjustable extension springs and the precision of the mechanism is finally improved in [25]. A gravity compensation algorithm is developed for the 7-DOF haptic interface in [26]. Most of the existing methods require precise parameters of the physical model and time-consuming derivation, especially for parallel mechanisms [27]. A calibration approach based on spatial interpolation is applied to extend the kinematic accuracy, and this method is also used for gravity compensation of the haptic device [28,29]. This provides satisfactory results while avoiding extensive calculations.

Although diverse methods have been developed for compensation, it remains critical for haptic devices to accurately and efficiently eliminate the adverse impact of gravity on force displays. To satisfy these requirements, passive and active compensation are adopted simultaneously as a hybrid method in this paper. In view of the gravitational calculation and analysis, an external mechanism combing pantographs and counterweights is designed for passive compensation. The adopted weights can be conveniently adjusted with respect to the applications, while strong robustness towards the parameter deviations between the desired and the actual value is provided. The workspace is spatially discretized and precisely calibrated as off-line data. The desired torques for an arbitrary configuration are calculated by interpolations in terms of the displacement to the vertexes. The accurate parameters of the physical model are not required, and the calculation process is straightforward. The decisions concerning the algorithm parameters for passive and active compensation are also discussed. The existing mechanism is Delta-like, with three translations as a haptic device for surgical robots. Finally, the corresponding experiments are carried out to confirm the feasibility and superiority of the proposed method.

2. Parallel Haptic Device for Surgical Robots

2.1. Delta-like Mechanism for Haptic Device

The haptic device was designed to provide three translations and a corresponding force display for the teleoperation of surgical robots, which is based on the Delta-like architecture. Compared to Delta, the novel architecture has the advantages of a larger workspace and a smaller space on the floor [12]. The proposed method for gravity compensation is applied in this device, but it is also applicable to others with similar mechanisms.

This mechanism is composed of one static platform, one moving platform, and two chains, as shown in Figure 1. The orientation of the moving platform remains constant because of the mechanical constraints between the two chains. Specially, an auxiliary component is added to enhance the mechanism's constraints. The chains possess an identical architecture, which consists of two parallelograms. The three translations of the system are finally driven by four motors on chains, which entails actuation redundancy. In practical applications, the operators hold the moving platform to perform the desired operations.



Figure 1. Parallel haptic device with Delta-like mechanism.

The forward and inverse kinematics can be solved by the constraints between the chains and the moving platform:

$$\vec{OC}_{i3} + \vec{C}_{i3}\vec{C}_{i2} + \vec{C}_{i2}\vec{C}_{i1} = \vec{OP}_e + \vec{P_eC}_{i1}$$
(1)

where C_{ij} is the *j*th connecting point on the *i*th chain; P_e stands for the spatial position of the end platform; O-XYZ is the global coordinate system.

According to the above constraint, the following equation can be obtained by solving the spatial position of C_{i1} :

$$\operatorname{tran}(x_e, y_e, z_e) \operatorname{tran}\left(0, (-1)^i \cdot l_{C_{i1}P_e}, 0\right) =$$

$$\operatorname{tran}(x_{i3}, y_{i3}, z_{i3}) \operatorname{rotz}(\theta_i) \operatorname{rotx}(\alpha_i) \operatorname{tran}(0, l_{C_{i2}C_{i3}}, 0) \operatorname{rotx}(\beta_i^1) \operatorname{rotz}(\gamma_i) \operatorname{tran}(0, l_{C_{i1}C_{i2}}, 0)$$
(2)

where (x_{i3}, y_{i3}, z_{i3}) and (x_e, y_e, z_e) are the spatial positions of the points C_{i3} and P_e in the global coordinate system, respectively; $l_{C_{i1}P_e}$ and $l_{C_{i1}C_{i2}}$ are the displacement between the corresponding points; α_i , β_i and γ_i are the active and passive joint angles in the *i*th chain.

Take the partial derivative of both sides of the above equation with respect to time, and the velocity conversion between the joints and the end is calculated as follows:

$$A_{6\times3}\cdot X = B_{6\times6}\cdot\dot{q}$$

$$A_{6\times3} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$B_{6\times6} = \begin{bmatrix} B_{3\times3}^1 & 0 \\ 0 & B_{3\times3}^2 \end{bmatrix}$$

$$B_{6\times6} = \begin{bmatrix} B_{3\times3}^1 & 0 \\ 0 & B_{3\times3}^2 \end{bmatrix}$$

$$B_{3\times3} = \begin{bmatrix} l_{1}sin\alpha_{i}sin\theta_{i} & -l_{2}cos\gamma_{i}sin\beta_{i}sin\theta_{i} & -l_{2}(cos\beta_{i}sin\gamma_{i}sin\theta_{i} + cos\gamma_{i}cos\theta_{i}) \\ -l_{1}sin\alpha_{i}cos\theta_{i} & l_{2}cos\gamma_{i}sin\beta_{i}cos\theta_{i} & l_{2}(cos\beta_{i}sin\gamma_{i}cos\theta_{i} - cos\gamma_{i}sin\theta_{i}) \\ l_{1}cos\alpha_{i} & -l_{2}cos\gamma_{i}cos\beta_{i} & l_{2}sin\gamma_{i}sin\beta_{i} \end{bmatrix}$$

$$(3)$$

where $X = \begin{bmatrix} x & y & z \end{bmatrix}^T$ is the position of the point P_e ; $q = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \alpha_2 & \beta_2 & \gamma_2 \end{bmatrix}^T$ is a matrix containing all angles of joints in chains; *J* stands for the full Jacobian matrix.

The Jacobian matrix can be also calculated by:

$$JX = q$$

$$= B_{6\times6}^{-1} \cdot A_{6\times3}$$
(4)

where $X = \begin{bmatrix} x & y & z \end{bmatrix}^T$ is the position of the point P_e ; $q = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \alpha_2 & \beta_2 & \gamma_2 \end{bmatrix}^T$ is a matrix containing all angles of the joints in the chains; *J* stands for the 6 × 3 full Jacobian matrix.

J

Note that all the joint angles are considered by the full Jacobian matrix and the active Jacobian J_a can be solved by removing the corresponding rows of passive angles γ_i :

$$J = \begin{bmatrix} J_{3\times1}^1 & J_{3\times1}^2 & J_{3\times1}^3 & J_{4\times1}^4 & J_{3\times1}^5 & J_{3\times1}^6 \end{bmatrix}^T J_a = \begin{bmatrix} J_{3\times1}^1 & J_{3\times1}^2 & J_{3\times1}^4 & J_{3\times1}^5 \end{bmatrix}^T$$
(5)

where $(J_{3\times 1}^k)^T$ is the *k*th row of *J*.

Thanks to the limited chains and simple architecture, the analytic solution of the kinematics can be obtained. The Jacobian matrix is also applied to calculate the force mapping between the end and the joints. The detailed derivations of the kinematics and the Jacobian matrix have been demonstrated in the previous work [30].

2.2. Gravity Compensation Based on Virtual Model

The gravity of the system is entirely sustained by motors on joints or operators in the case of an absence of passive compensation [31]. The gravitational torques are calculated by the virtual displacement method, and the mass properties of the components are derived by the 3D model. The calculation is carried out in terms of the single chain and the end platform.

The diagram of the *i*th chain and the mass properties of the components are shown in Figure 2.

The total potential energy of the system *E* is solved by:

$$E = \sum_{i=1}^{2} \sum_{j=1}^{5} E_{ij} + E_e \tag{6}$$

where E_{ij} and E_e are the potential energy of the *j*th components on the *i*th chain and the end platform, respectively.

The potential energy E_{ij} can be calculated by:

$$E_{ij} = m_{ij}gz_{ij} \tag{7}$$

where m_{ii} is the mass of the *j*th component on the *i*th chain and z_{ij} is the corresponding coordinate along the Z-axis; g is the gravitational acceleration.



Figure 2. Diagram of the *i*th chain and mass properties of components.

The corresponding coordinate along the Z-axis is solved as:

$$\begin{bmatrix} z_{i1} \\ z_{i2} \\ z_{i3} \\ z_{i4} \\ z_{i5} \end{bmatrix} = \begin{bmatrix} C_{i3}P_{i1}sin\alpha_i \\ C_{i3}P_{i2}sin\beta_i \\ C_{i3}C_{i2}sin\alpha_i - C_{i2}P_{i3}cos\gamma_i sin\beta_i \\ C_{i3}C_{i2}sin\alpha_i - C_{i2}P_{i4}sin\beta_i \\ C_{i3}C_{i2}sin\alpha_i + C_{i3}C_{i4}sin\beta_i \end{bmatrix}$$
(8)

where α_i and β_i are the angles of the first and the second active joints, respectively; γ_i is the angle of the third passive joint.

The required torques of the joints can be solved by the partial derivative of the total potential energy with respect to the corresponding angle:

$$\begin{bmatrix} t_{i1} \\ t_{i2} \\ t_{i3} \end{bmatrix} = \begin{bmatrix} (m_{i1}C_{i3}P_{i1} + m_{i3}C_{i3}C_{i2} + m_{i4}C_{i3}C_{i2} + m_{i5}C_{i4}P_{i5})g\cos\alpha_i \\ (m_{i2}C_{i3}P_{i2} - m_{i3}C_{i2}P_{i3}\cos\gamma_i + m_{i4}C_{i2}P_{i4} + m_{i5}C_{i3}C_{i4})g\cos\beta_i \\ m_{i3}gC_{i2}P_{i3}\sin\gamma_i\sin\beta_i \end{bmatrix}$$
(9)

where t_{ij} is the required torque of the *j*th joint on the *i*th chain.

The required force $F_e = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix}^T$ on the end is calculated by combing the chains and the moving platform: F

$$F_e = J^T M_c + F_m \tag{10}$$

where $M_c = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{21} & t_{22} & t_{23} \end{bmatrix}^T$ is the matrix composed of the joint torques caused by the component weights in the corresponding chain; $F_m = \begin{bmatrix} 0 & 0 & m_e g \end{bmatrix}^T$ is the balance force of the moving platform. In the case of an absence of passive compensation, the overall forces are realized by the operators, which is an enormous burden and accelerates fatigue.

The active Jacobian is 4×3 and it is not a square matrix because the mechanism is actuated by four motors to realize three spatial translations. The required joint torques $M_a = \begin{bmatrix} t_{11}^a & t_{12}^a & t_{21}^a & t_{22}^a \end{bmatrix}^T$ caused by external forces F_e on the point P_e are commonly solved by the following equation:

$$M_a = \left(J_a^T\right)^+ F_e \tag{11}$$

where t_{ij}^a is the torque of the *j*th active joint in the *i*th chain; $(J_a^T)^+$ is the pseudo-inverse of J_a^T . This arrangement is adopted to minimize the sum of the squares of the required torques M_a .

3. Passive Gravity Compensation with Constant Force

Passive compensation is introduced in this section as the first process because of the distinct improvement to the peak capability of the force display. Full gravity compensation can be achieved by four elastic systems for the Delta-like mechanism, but it is difficult to implement due to the extensive modification and inadequate assembly space [20]. An approximate compensation is more feasible for the Delta-like mechanism in consideration of the effect and the implementation's difficulty.

According to previous calculations, most of the gravity is concentrated in the direction of the *Z*-axis. Therefore, an invariant vertical force is applied on the end to directly reduce the physical burdens of operators as a basic strategy for passive compensation. The compensation mechanism is designed, and the involved parameters are optimized in this section.

3.1. Mechanism Design of Passive Compensation

The mechanism for passive compensation is devised to exert a constant vertical force on the end without compromising the kinematic performance of the original haptic device. A sufficient workspace for the compensation mechanism is required to ensure the validity of the haptic device with an arbitrary configuration, while the design and assembly should be seriously considered to avoid potential interferences between components.

These requirements are satisfied by the combination of pantographs and a 2R1T architecture. The pantographs with large expansion and contraction shown in Figure 3a are adopted to provide a sufficient workspace. The 2R1T mechanism is articulated with pantographs at the points P_0 and P_m , respectively. The pantographs are connected to the moving platform of the haptic device by two revolute joints at P_n . The proposed mechanism possesses a leverage property, where P_0P_n is always a multiple of P_0P_m at any configuration. The combining mechanism, which provides three translations, is shown in Figure 3b. The motion along the Z-axis is decoupled with the horizontal axis and the corresponding force. The following equation can be obtained according to the leverage property:

$$\frac{f_m}{f_n} = \frac{P_n P_0}{P_m P_0} \tag{12}$$

where f_m and f_n are the forces along the Z-axis at the points P_m and P_n , respectively.



Figure 3. Compensation mechanism combining (a) pantographs and (b) the 2R1T architecture.

The final system with a passive compensation is shown in Figure 4. The compensation mechanism is symmetrically arranged to avoid asymmetrical forces. The constant force along the *Z*-axis is realized by counterweights fixed at P_m . No special requirement is emphasized for the assembly dimension, and only potential interferences should be avoided. In terms of the leverage property, the ratio $P_n P_0 / P_m P_0$ is set to be 2 for reasonable assembly and a compact design.



Figure 4. Final system with passive compensation.

Benefitting from the leverage property, the pantographs are approximatively balanced by their own weights. The residual terms can be removed by fewer counterweights and a rational design.

Minor modifications to the original mechanism are required in this solution and it is more feasible for existing equipment. The counterweights on the end can be determined by the actual prototype and mission. Compared with the conventional approaches, such as springs or a counterweight in chains, this method provides stronger adjustability in practical applications.

3.2. Parameter Optimization

In order to achieve the best compensation effect, the design parameters are optimized by a multi-objective genetic algorithm on the basis of a numerical simulation. The motion of the haptic device is determined by operators in terms of the mission, and the configuration with respect to the whole workspace should be taken into account.

Due to the partial decoupling property of this mechanism, the results of the compensation force are free with respect to the assembly dimension. The force f_n on the end is set to be the only design parameter and the global workspace with discretization configurations is assigned as the optimization domain. The purpose of passive compensation is to reduce the gravitational loads of the joints and improve the output capability. The global maximum torque of all the joints and the absolute value of f_n are calculated as the fitness. The global maximum torque is adopted to obtain the best compensation, while the absolute value of f_n is employed to limit the weight. By means of a multi-objective genetic algorithm, the optimization process is carried out to minimize the fitness function, and the results are shown in Figure 5.



Figure 5. Optimization results of passive gravity compensation.

It appears that the compensation effect is reduced as the adopted force decreases. The global maximum torque is lower by 79.98% in the case of $f_n = 3.20$ N, while the output capability is improved. The forces along the *Z*-axis and the maximum torque of all the joints in the case of no compensation and passive compensation are demonstrated in Figure 6.



Figure 6. Results of no compensation and passive compensation.

The results reveal that the required balance force is directly reduced by the compensation mechanism. The negative force implies that the gravitational loads along the *Z*-axis are completely removed, and the compensation leads to opposite effects in some configurations. The loads of the joints are lowered, and the residual values are associated with the coordinates along the *Z*-axis.

The compensation's effectiveness is confirmed by the results of the optimization, and the parameter can finally be determined according to the practice load. It is also satisfactory for haptic devices to provide larger outputs for teleoperation systems [32,33].

4. Active Gravity Compensation

The loads of the joints have been greatly reduced by passive compensation and the active algorithm is presented in this section to eliminate the residual terms. Although

the required force can be solved by previous calculations based on the virtual model, the deviation between the virtual model and the physical prototype may lead to inaccurate results. The active compensation in this paper is based on the calibration of the meshing vertexes and interpolation calculations.

4.1. Calibration and Interpolation

The required forces vary continuously as the configuration of the haptic device changes, and it possesses limited variation between close configurations. This property can be adopted to develop the active compensation algorithm. The global workspace is discretized into a combination of spatial cubes and the required forces of different configurations at the vertexes of the cubes are precisely calibrated as shown in Figure 7.



Figure 7. Discretized workspace and linear interpolation.

The results in an arbitrary configuration are calculated by linear interpolation, and in the one-dimensional case, the result at D can be solved as:

$$F_D = w_1^0 F_1 + w_2^0 F_2 \tag{13}$$

where w_i^0 and F_i are the weight and the required force of the *i*th vertex, respectively. The weights of different vertexes are determined based on the displacements to the required point:

$$v_1^0 = 1 - \frac{AD}{AB} \\ v_2^0 = 1 - \frac{BD}{AB}$$
(14)

In the three-dimensional case, the force to be calculated is modified as:

7 7

$$F_D = \sum_{i=1}^8 w_i^0 F_i$$
 (15)

The weight is solved as a combination of three dimensions:

$$w_i^0 = (1 - \frac{|\Delta x_i|}{d_x})(1 - \frac{|\Delta y_i|}{d_y})(1 - \frac{|\Delta z_i|}{d_z})$$
(16)

where Δx_i , Δy_i , and Δz_i are the displacement between the *i*th vertex and the arbitrary configuration in the corresponding dimension; d_x , d_y , and d_z are the lengths of the cube. This arrangement results in the following properties:

(1) When point D coincides with a vertex, the corresponding weight is 1 and the remaining terms are 0;

(2) The sum of the overall weights $\sum_{i=1}^{8} w_i^0$ is 1.

Nevertheless, at configurations near the boundary, partial vertices of the calibrated cubes may be missing, which leads to failed calculations. In order to address this problem, the weights are revised as follows:

$$w_{i} = \frac{w_{i}^{0}k_{i}}{\sum_{i=1}^{8}w_{i}^{0}k_{i}}$$
(17)

where k_i is the validity index of the *i*th vertex. It is 1 only if the corresponding vertex is reachable, and 0 otherwise.

4.2. Parameter Determination

In active compensation, the workspace is divided into discrete cubes. Obviously, the smaller the volume of the cube, the higher the accuracy of the interpolation, but the larger the calculation quantities. The determination principle of the spatial grid is elaborated in this section to ensure the desired accuracy with an acceptable calibration time.

The maximum deviation in an arbitrary configuration between the required forces and the interpolation results can be expressed as:

$$|F_a - \sum_{i=1}^8 w_i F_i||_{\infty} \le \varepsilon \tag{18}$$

where F_a denotes the actually required compensation forces and ε is the desired threshold. The following derivation is carried out:

$$\|F_a - \sum_{i=1}^8 w_i F_i\|_{\infty} = \|\sum_{i=1}^8 w_i (F_a - F_i)\|_{\infty} \le \sum_{i=1}^8 w_i \|F_a - F_i\|_{\infty}$$
(19)

It appears that the desired accuracy can be satisfied as the following equation is realized:

$$\|F_a - F_i\|_{\infty} \le \varepsilon \tag{20}$$

The results imply that the deviations between the calculated configuration and vertices of the corresponding cube should be less than the threshold. Several sampling points are adopted as the center points of each cube and the deviations are calculated with different distribution densities in terms of Equation (17). The density is gradually decreased until the maximum deviation of all the sampling points is larger than the threshold. The results of the numerical simulations are shown in Figure 8.

The best accuracy is realized with the smallest grid spacing and the maximum deviation increases as the density decreases. The number of configurations to be calibrated in the case of $d_{xyz} = 5$ mm is extremely large and it is not feasible in practice. The desired threshold is set to be 0.1 N according to the requirements of haptic devices for surgical robots. The grid spacing is finally determined to be 20 mm, while the maximum deviation of all the sampling points is 0.097 N. In this case, the number of points to be calibrated is 3023, which provides satisfactory results with an acceptable degree of time consumption.



Figure 8. Deviations of compensation force with different grid spacings.

5. Experiments

The experiment is carried out to verify the feasibility of the proposed method, while the adopted prototype of the haptic device with three DOFs is shown in Figure 9. A force sensor is fixed on the moving platform as a component of the system, which is accounted for by gravity compensation.



Figure 9. Prototype of the haptic device for experiments.

The active joints are driven by DC motors and the motion control card. Cables are employed for transmission instead of gears, which possess lower friction and higher backdrivability.

Counterweights are fixed to the pantographs to provide constant forces for passive compensation. The weights can also be conveniently adjusted in the practical applications, which is one advantage of this approach. In view of the dynamic performance, the adopted counterweights are 0.32 kg in total.

The global workspace is discretized as cubes separated by 20 mm and the haptic device is driven to reach the configuration at each vertex one by one. The motion process lasted for 2 s, and then stopped for 1 s to stabilize the mechanism and record the maintenance torques of motors. The required forces are calculated by interpolation in terms of Equation (8). The calibration process is conducted in the case of both no compensation and passive compensation. The maximum torques of all the motors are partially shown in Figure 10.



Figure 10. Maximum torques of joints in the case of no compensation and passive compensation.

It appears that the loads of the motors are significantly reduced by passive compensation and that this method provides an effective compensation in the global workspace. The global maximum torque is lowered by 45.43%, while the peak capability of the force display is enhanced.

The combined approach is eventually applied to the haptic device to compensate for the residual gravity. Based on previous off-line calibrations, the required torques of the motors in an arbitrary configuration are calculated in real time. Thus, the configuration of the haptic device can remain constant without external forces, which is the best effect for gravity compensation. Possible deviations are offset by frictions in the joints, which are extremely small and have a slight effect on the operation. This implies that static balance is achieved and the detrimental effect of gravity on the force display is completely removed. The handle of the haptic device is randomly manipulated in different cases for comparison, and the forces along the *Z*-axis are shown in Figure 11.

In the case of no compensation, the required force along the *Z*-axis is more than 8 N, which entails intense physical exhaustion for a long operation. In teleoperation applications, haptic devices are utilized at low speeds. Although the inertia of the system is increased, the passive compensation remains effective, according to the results of the force sensor, and the maximum force along the *Z*-axis is reduced by 41.96%. As a result of the combined approach, the maximum force is lowered by 94.98% and only less than 0.49 N is required. The capability of the force display is further tested at the constant configuration. The desired force is set to be 6 N along the *Z*-axis and the results are shown in Figure 12.

The force deviation is less than 0.6 N for the three axes, which is caused by joint frictions. It seems that the residual gravity is significantly reduced, and the accuracy of the force display is greatly extended.



Figure 11. Required forces along the *Z*-axis with random configurations in the case of no compensation, passive compensation, and combined compensation.



Figure 12. Feedback forces with combined compensation.

6. Discussion

Passive compensation with counterweights on the end has proven to be effective to reduce the load of motors and enhance the capability of the force display. Compared with the conventional approach with springs or counterweights on linkages, it possesses considerable effects, a convenient assembly, and strong adaptability. The residual gravity terms are further compensated by calibration and interpolation, while the feasibility has been verified by experiments. Detailed derivation and calculations are not required in this approach, and it is easy to combine with other compensations.

According to the experimental results, the gravity of the system is completely compensated by the combined method with advantages of a simple principle and easy implementation. No detailed derivation and complicated calculation are required by the compensation process, while the mechanism system is used as a black box. The proposed method is also applicable to different types of equipment for various missions.

The following advantages are also conferred by passive compensation:

• It is especially suitable for the existing devices. The compensation mechanism can be assembled as an external attachment, and a major modification is not required. In conventional approaches such as springs, the compensation mechanism is fixed on chains, and the internal modification is complicated.

- It is convenient to adjust in terms of the actual prototype for desired results. In practical applications, the end executor is not always constant. The parameter of the proposed method can be changed to deal with different cases.
- It is effective for approximate compensation in all configurations, which implies strong robustness.

The active compensation method is based on the physical prototype and the deviations between the theory and the practice model thereby are avoided. Although the initial calibration is time-consuming, this process is performed only once. The program running online is concise, and its efficiency is still acceptable in consideration of the compensation effect. In addition, this method provides a perfect combination of other passive compensations.

The proposed combined method is suitable for haptic devices with only translations, which is an informed limitation. The compensation for mechanisms with orientations is challenging work due to the complex nonlinearity. Future studies may develop feasible compensation schemes for devices with both translations and orientations.

7. Conclusions

The peak capability and accuracy of the force display are significant for haptic devices in teleoperations. Passive compensation requiring no extra energy is achieved by counterweights on the end and pantographs, which reduce the loads of the motors. In spite of the increased inertia, it remains effective in the global workspace. The maximum torque of the motors is reduced by 45.43% and the required force is lowered by 41.96% according to the experimental results. Gravity is the primary disturbance to the force display's accuracy, and the residual term is further eliminated by active compensation. The method adopted in this paper provides substantial performance with an understandable principle, simple formulas, and a conventional implementation. The algorithm's parameters are determined by the desired accuracy and the amount of calculation. As a result, the configuration of the haptic device can remain constant in an arbitrary configuration and the accuracy of the force display is observably improved.

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