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Compliant Humanoid Robot Control by the Torque Transformer

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Abstract— **This paper presents a new control architecture for compliant motion control and safe physical interaction between humanoid robot and human. One of the key technologies in this framework is the Torque Transformer, which enables the implementation of joint torque control on the traditional joint position controlled robots. In this framework, the torque control is accomplished by converting desired joint torque command into instantaneous increments of joint velocity command. Through the transformer, the Operational Space Formulation was applied to account for the dynamics of the system on the current joint position controlled robots. This approach was experimentally implemented on the physical humanoid robot, HONDA ASIMO's upper body control. The ZMP based stable balance controller of ASIMO was integrated to control the lower body of the robot. In this framework, dynamics control by the torque transformer and stable position based balance controller were connected and coordinated together on the current position controlled humanoid robot. The paper presents modeling process of the torque transformer, whole body controller and the results of the implementation which demonstrate the effectiveness of this approach.**

I. INTRODUCTION

ROBOTS are multi-body systems whose dynamics is nonlinear and highly coupled. Robotic control is most frequently accomplished with a position control system. In this framework, desired motion is designed for every task so that the robot can accomplish its motion by following the designed trajectory. An individual joint position command is calculated by applying inverse kinematics to the end-effector's position command in Cartesian space. Typical position controller with PD control is implemented for each motor level controller and the joint position command is achieved by high gain control. This approach has been well suited in factory automation because accuracy and fast responses are the most important function to achieve the required tasks.

Different from the factory robots, the humanoid robots [1][2][3][4] are supposed to work in our daily environment. Compliant motion control is one of the critical problems when the robot moves in our environment because the work space of the robot is very narrow, complicated and unpredictable. In the actual environment, unpredictable contact will happen between the robot and the environment or human. So far, the traditional position control system has been applied to most of the humanoid robots. However, the position controller cannot account for the dynamics of the system. The dynamic coupling effects are treated as a disturbance and it limits the performance of high speed precise trajectory tracking and compliant motion control.

There are few human-sized humanoid robots developed for compliant and physical contact with human. Compliant motion control was achieved with sensors and was implemented on the wheel based robot. For example, Robovie-II [5] was designed for communication with human which is necessary to participate in our daily life. The main feature of the Robovie is natural communication and physical interaction with human. TWENDY-ONE of Waseda Univ. was developed to coexist with human in our daily environment. The robot is designed to support our activity through natural communication. The main feature of the TWENDY-ONE is high response and adoptive motion control in case of the physical contact with human. As for the biped humanoid robots, HRP-2 robot [3] can support human carrying the panel. Compliant position control was applied to the hands and locomotion for contacts with modeled environment. Whole body contact motion of a humanoid robot was proposed by using full-body distributed tactile sensor [6]. However, compliant motion control and accurate task control has not been achieved. To realize more advanced physical interaction with human, compliant and passive motion control is one of the key technologies for the humanoid robot. Moreover, the humanoid robots should accomplish its multiple tasks on the stable balance controller.

One approach for addressing this problem is to provide torque control. The input torque for the system can be designed to compensate for dynamic effect of the system. Decoupled task dynamics can be applied by the Operational Space Formulation which provides the robot with higher performance in position tracking as well as in compliant motion. Therefore, advanced performance, complex behaviors and compliant posture control can be implemented for robots if torque control is applied.

The proposed ***Torque Transformer*** provides a method to control the existing position controlled system by torque command and to compensate dynamic effect of the system in the motion controller. In this paper, the torque transformer is defined and modeled through the analysis of the internal motor control unit. It was implemented to HONDA ASIMO's upper body control and validated through the experimental test. On the other hand, to realize the accurate balance control, the HONDA ASIMO's current balance controller was integrated to this framework. Compliant upper body control and stable lower body control were coordinated together to realize compliant and physical interaction with human. All the functions were implemented on the existing position controlled system without hardware modification.

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II. TORQUE CONTROL

A. *Proposed System*

Torque to Position Transformer [7] was developed to convert desired joint torque command into instantaneous increments of joint position command. The merit of this framework was that (i) the open-loop torque control can be realized on the current position controlled robot without hardware modification and (ii) the controller can account for nonlinear dynamics of the system. In this framework, the Operational Space Formulation was applied to account for the dynamics of the robot. The concept of the transformer was analyzed and validated on the HONDA ASIMO robot [8][9][10]. In this framework, the transformer was defined as the inverse model of the internal motor control unit and works to transfer the joint torque command into the motor current command by cancelling the effects of the inner feedback loops.

Position Command to Motor

The inverse model of internal motor controller can also be applied using the velocity command input to the motor control unit. In this paper, Torque to Velocity Transformer, which transforms the joint torque command into the joint velocity command, is proposed as ***Torque Transformer***. Fig. 1 shows the framework of the proposed control system**.** The left block shows the Motion Controller of the application software level in which, dynamics controller by the Operational Space Formulation is defined. In the right block, the joint position controller is defined as the hardware level controller. In the joint position controller, the ideal position control unit $D^*(s)$ and the resulting physical joint $G^*(s)$ are defined. The inverse model of the ideal position control unit, $D^*(s)$, is applied as *Torque Transformer*, T2, which transforms a torque command into an instantaneous velocity command. In this framework, position command is ignored by commanding a joint position actual or by commanding position gain as zero. Through frequency analysis or identification of the individual motor controller, the transformer has to be identified previously. Once this inverse model is generated, the torque command is directly sent to the motor current command i_{cmd} by cancelling the effects of the inner feedback loops.

B. *Motor Controller*

To model the Torque Transformer in Fig. 1, the internal motor control unit, $D^*(s)$, must be identified precisely by the block diagram of the system or frequency analysis of the system. In Fig. 2, a block diagram of a joint position control unit, $D^*(s)$, is shown. The inputs to the motor controller are a position command $q_{cmd/mot}$ and a velocity command $\dot{q}_{cmd/mot}$ which are designed by the motion controller in Fig. 1. Generally, to control the motor, PD controller is implemented for each position control unit. The position control unit has a position feedback loop and a velocity feedback loop in which feedback data is measured by the sensor. Actual position is measured by an encoder sensor or a potentiometer, etc., which is generally attached to the motor as a unit. Actual velocity is measured by a velocity sensor or calculated by actual position data. To improve quick response of the motor control, a velocity feedforward command is applied to the velocity feedback loop and velocity gain is adjusted for every motor. In the current feedback loop in Fig. 2, the current gain KC is composed of a current proportional gain K_{ip} and a current integral gain K_{ii} and negative feedback loop is closed by subtracting the actual current, i_{mot} . The term AL represents armature losses and is defined as $1/(L_m s + R_m)$. Here, R_m is motor resistance and L_m is motor inductance. The term KE is back electromotive force which is generated by the actuation of the motor. Motor torque is calculated by multiplying torque constant KT with actual current, i_{mot} . The term IF is composed of rotor inertia J_m and rotor friction B_m and is defined as $1/(J_m s + B_m)$. The motor is controlled by this framework and the physical joint PJ is actuated according to the commands with high gain feedback control.

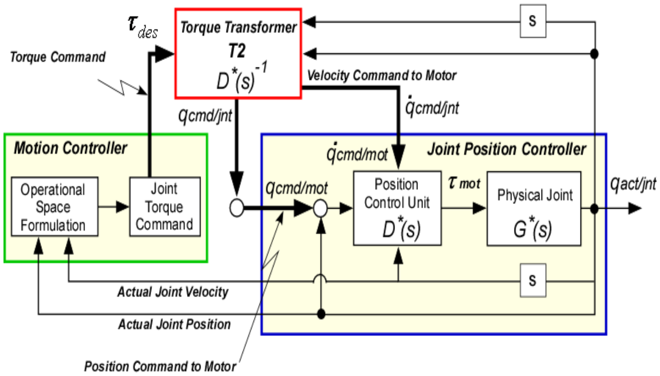


Fig.1 Framework of the proposed torque control system. The inverse model of the control unit is applied as the *Torque Transformer*, T2, which transforms a torque command into an instantaneous velocity command.

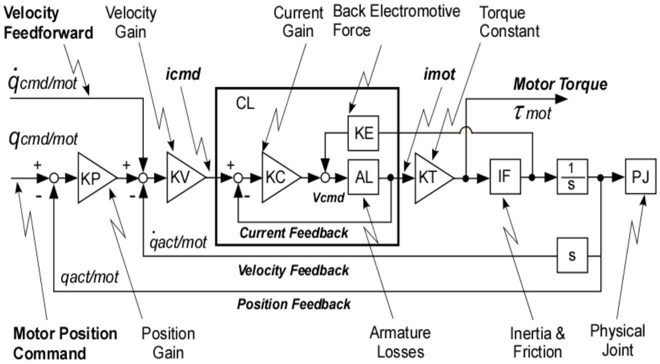


Fig. 2 Position control unit. Generally, the motor controller is composed of a position feedback loop, a velocity feedback loop and a current feedback loop to drive the position error to be zero.

C. Modeling of the Control Unit

In Fig. 1, the joint position controller is defined by the ideal position control unit, $D^*(s)$, the resulting physical joint, $G^*(s)$ and the effective torque τ_{eff}. As for the dynamics of the joint, $G^*(s)$ is given by

$$I_{eff}\ddot{q} + B_{eff}\dot{q} + N(q,\dot{q}) = \tau_{eff} \tag{1}$$

Here, I_{eff} is the effective moment of inertia, B_{eff} is the effective linear friction coefficient and τ_{eff} is the effective motor torque at the joint output. The term $N(\theta,\dot{\theta})$ is the nonlinear effect in the joint dynamics. These effective values are calculated by using the mechanical properties of the system and combine the properties of the motor, the link and gear ratio.

Here, we estimate the position feedback loop to be ignored by commanding joint position actual, $q_{act/jnt}$, into the joint position command or by commanding joint position gain as zero. In this case, relationship between the velocity command $\dot{q}_{cmd/mot}(s)$ and resulting velocity $\dot{q}_{act/mot}$ in the joint position control unit can be represented by a closed loop transfer function.

$$T(s) = \dot{q}_{act/mot}(s)/\dot{q}_{cmd/mot}(s) \tag{2}$$

The effective torque, τ_{eff}, at the joint is given by

$$\begin{aligned}\tau_{eff}(s) &= D^*(s)(\dot{q}_{cmd/mot}(s) - \dot{q}_{act/mot}(s))\\ &= D^*(s)\cdot\dot{q}_{cmd/mot}(s)(1-T(s))\end{aligned} \tag{3}$$

In cases where nonlinear effects at the joint are negligible, it is sufficient to represent $D^*(s)$ and $G^*(s)$ as linear transfer functions in terms of model accuracy. In this case, $\tau_{eff}(s)$ is calculated as $\tau_{des}(s)$.

In cases where nonlinear effect has to be considered at the joint, $T(s)$ cannot be computed analytically because of the nonlinear nature of the joint. However, it can be experimentally identified from frequency analysis of the response in the feedback control system. The effective torque, $\tau_{eff}(s)$, can be viewed as the torque associated with the linear portion of the dynamic system.

$$G^*(s) = \frac{1}{I_{eff}s^2 + B_{eff}s} \tag{4}$$

Given the identified closed loop transfer function $T(s)$ and $G^*(s)$, the effective controller can be computed as follows:

$$D^*(s) = \frac{T(s)}{G^*(s) - T(s)\cdot G^*(s)} \tag{5}$$

The effective torque τ_{eff} at the joint is determined as desired dynamic torque τ_{des} if the ideal position control unit $D^*(s)$ is identified. From Equation (3), we can determine the position input $q_{cmd/mot}(s)$ corresponding to a desired dynamic torque $\tau_{des}(s)$ as follows:

$$\begin{aligned}\dot{q}_{cmd/mot}(s) &= \frac{\tau_{des}(s)}{D^*(s)} + \dot{q}_{act/mot}(s)\\ &= \frac{\tau_{des}(s)}{D^*(s)(1-T(s))}\end{aligned} \tag{6}$$

In Equation (6), $D^*(s)^{-1}$ is an inverse model of the internal motor controller and shows the relationship between the velocity command and the resulting velocity. Therefore, Equation (6) is defined as the Torque Transformer.

D. Derivation of the transformer

The purpose here is to derive $D^*(s)$ in Equation (6). In this framework, nonlinear effect is defined as negligible and the system can be analytically defined by a block diagram and the dynamic parameters of the motor. In the proposed framework, motor position command is commanded by actual motor position $q_{act/jnt}$ or the motor position gain is commanded as zero to cancel the effect of the position feedback loop in Fig. 2.

$$\begin{gathered}q_{cmd/mot}(s) = q_{act/mot}(s)\\ K_p = 0\end{gathered} \tag{7}$$

According to the motor block diagram in Fig. 2, current command, i_{cmd}, becomes :

$$i_{cmd} = K_v\cdot(\dot{q}_{cmd/mot}(s) - \dot{q}_{act/mot}(s)) \tag{8}$$

Here, K_v is a velocity gain. On the other hand, the motor generates the torque through its actuation. The motor torque is defined as follows.

$$\tau_{eff} = K_t\cdot i_{mot} = K_t\cdot CL\cdot i_{cmd} \tag{9}$$

Where CL is the transfer function of the current feedback loop and K_t is the motor torque constant. By Equation (8) and (9), $\tau_{eff}(s)$ is defined as follows.

$$\tau_{eff} = K_v\cdot K_t\cdot CL\ \cdot(\dot{q}_{cmd/mot}(s) - \dot{q}_{act/mot}(s)) \tag{10}$$

Therefore, the relation between the motor position and the motor torque is defined by Equation (10). By replacing τ_{eff} by $\tau_{cmd/mot}$, $\dot{q}_{cmd/mot}$ is defined as follows:

$$q_{cmd/mot}(s) = q_{act/mot}(s) \text{ or } K_p = 0$$

$$\dot{q}_{cmd/mot} = \frac{\tau_{cmd/mot}}{K_v\cdot K_t\cdot CL} + \dot{q}_{act/mot} \tag{11}$$

Equation (11) is defined as the Torque Transformer of motor control level when nonlinear effect is defined as negligible. Generally, a gear is mounted on the joint to amplify the output torque and to reduce the output velocity of the motor. In Equation (12), the Torque Transformer is modified as joint level equation by adding the definition of gear ratio, η.

$$q_{cmd/jnt}(s) = q_{act/jnt}(s) \text{ or } K_p = 0$$

$$\dot{q}_{cmd/jnt} = \frac{\tau_{cmd/jnt} + \tau_{friction}}{K_v \cdot K_t \cdot CL \cdot \eta^2} + \dot{q}_{act/jnt} \qquad (12)$$

If the joint friction, which is mainly caused by the gear system, affects the Torque Transformer, joint friction model, $\tau_{friction}$ can be modeled by the traditional friction model [12]. Or the term $K_v \cdot K_t \cdot CL \cdot \eta^2$ in Equation (12) can be experimentally identified from frequency analysis of the feedback control system. Equation (12) can be also simplified by assuming the transfer function of the current feedback loop CL to be equal to 1 because response of the closed loop is much faster than the position feedback loop.

E. Analysis of the Torque Transformer

The effect of proposed Torque Transformer and previous Torque to Position Transformer [7] is shown in Fig. 3. In general, some joint position control unit (Fig.1), which is defined as hardware level, has faster servo frequency than the motion controller of application software level. In this case, when the toque command is generated and sent to the position control unit through the Torque Transformer, the measured actual position and the velocity from the hardware changes more. The effect of the feedback loop can't be canceled correctly by the transformer. It is more typical for Torque to Position Transformer because there are two feedback loops which need to be cancelled. If the proposed Torque Transformer is applied, position feedback loop can be ignored by commanding Kp as zero. Therefore, the proposed Torque Transformer works better than the Torque to Position Transformer.

If the Equation (11) is commanded into the joint position control unit (Fig. 3), the Equation (11) will transfer the torque command, $\tau_{cmd/mot}$, to the current feedback loop cancelling the effect of the feedback loop and gains. According to Equation (9), $\tau_{cmd/mot}/K_t \cdot CL$ is the current command to the CL which can be modeled according to the current control system.

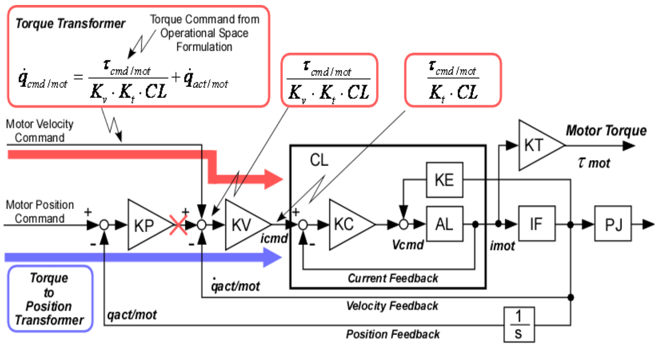


Fig. 3 Analysis of the Torque Transformer. The blue arrow shows previous Torque to Position Transformer and the red arrow shows proposed Torque Transformer.

III. UPPER BODY CONTROL

A motion module is reconstructed with the Operational Space Formulation [13] to calculate the dynamics of the robot. Generally, the joint space dynamics of a robot are described by

$$A(q)\ddot{q} + b(q,\dot{q}) + g(q) = \Gamma \qquad (13)$$

where q is the $n \times 1$ generalized vector in joint space, $A(q)$ is the $n \times n$ mass/inertia matrix, $b(q,\dot{q})$ is the Coriolis and centrifugal torque and $g(q)$ is gravity torque. Corresponding to the instantaneous linear/angular velocity, ϑ, in task space, the following relationship is defined by the Jacobian, $J \ (q)$.

$$\vartheta = J(q) \cdot \dot{q} \qquad (14)$$

Task dynamic behavior is obtained by projecting the joint space dynamics into the space associated with the task:

$$\Lambda(q)\dot{\vartheta} + \mu(q,\dot{q}) + p(q) = F \qquad (15)$$

here, $\Lambda(q)$, $\mu(q,\dot{q})$ and $p(q)$ are the inertia matrix, the vector of Coriolis/centrifugal forces and the vector of gravity forces mapped into the operational space and are defined as follows;

$$\Lambda(q) = (JA^{-1}J^T)^{-1}$$
$$\mu(q,\dot{q}) = \Lambda(JA^{-1}b - \dot{J}\dot{q})$$
$$p(q) = \Lambda JA^{-1}g \qquad (16)$$

The control force, F, in Equation (15) provides a decoupled control structure by

$$F = \hat{\Lambda}(q)f^* + \hat{\mu}_t(q,\dot{q}) + \hat{p}(q) \qquad (17)$$

where $\hat{\cdot}$ represents estimates of the model parameters. f^* is the command to the unit mass system. When the estimates are perfect, the following decoupled equations of motion for the end-effector are obtained.

$$\dot{\vartheta} = f^* \qquad (18)$$

The Operational Space Formulation provides decomposition of joint forces into two control vectors; (i) the joint torque corresponding to forces acting at the task and (ii) joint torque that only affects the posture behavior in the null space.

$$\Gamma = \Gamma_{task} + \Gamma_{posture} = J^T F + N^T(q)\Gamma \qquad (19)$$

Here, $N^T(q)$ is the dynamically consistent null space projection matrix.

$$N^T(q) = I - J^T \bar{J}^T \qquad (20)$$

$$\bar{J}^T = \Lambda JA^{-1} \qquad (21)$$

The term, $N^T(q)$, guarantees that the null space control torque will not generate any force on the task control. The Operational Space Formulation is applied to the upper body control of ASIMO (Fig. 4).

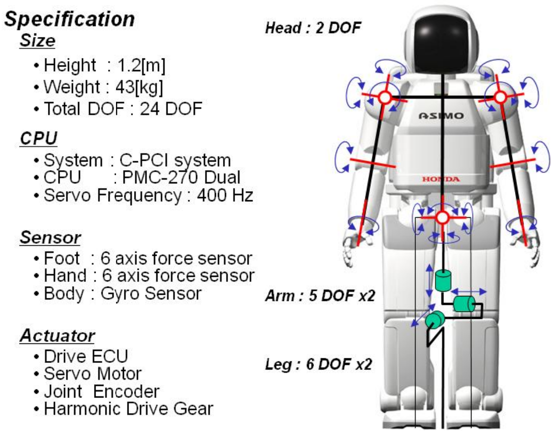


Fig. 4 The specification of HONDA ASIMO which was used for the experimental validation. Dynamics model is applied for the upper body of the robot. The lower body is controlled by the ZMP based HONDA balance controller. The upper dynamics controller and the lower body ZMP based balance controller are coordinated together in this framework.

IV. LOWER BODY CONTROL

A. *Balance Control*

To achieve the stable balance control while the robot is standing or walking, the following technologies needed to be addressed.

a) Not falling down even when the floor is uneven.
b) Not falling down even when pushed.
c) Being able to stand and walk stable on stairs or slopes.

This framework is achieved by the following three posture controls which are main feature of HONDA ASIMO.

1. Floor Reaction Control
2. Target ZMP Control
3. Foot Planting Location Control

If the unpredicted element causes the instability of the balance, these three control systems operate to prevent the robot to fall and recover the balance of standing and walking.

When the robot is walking, it is influenced by inertial forces caused by the gravity and the acceleration and deceleration of walking. These combined forces are called the total inertial forces. Floor Reaction Force is a reaction force from the floor when the robot's foot contacts the floor. The intersection of the floor and the axis of the total inertial force have a total inertial force moment of zero. It is called Zero Moment Point. The total internal force of the ideal walking pattern is called the target ZMP. When the robot is maintaining perfect balance while walking, the axis of the target total inertial force and the actual floor reaction force are the same (Fig. 5). Therefore, Target ZMP and the center of ground reaction force are the same.

In the proposed framework, the ASIMO's walking controller works to realize the stable balance control [2]. The robot intends not to walk, however, the precise balance control of ASIMO's ZMP based controller is required to control the balance of lower body. It is also necessary to compensate the gravity vector for upper body dynamics controller. The orientation and the acceleration are measured by a gyro sensor and the position and orientation of the torso is modified with kinematical estimation. The modification process is shown in Fig. 6.

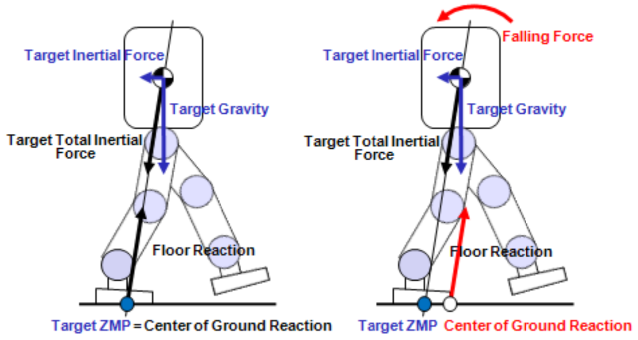


Fig. 5 Target ZMP and center of ground reaction force.

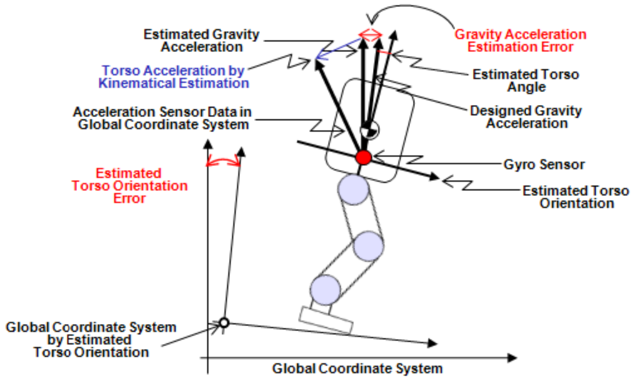


Fig. 6 Adjustment of computation of gyro sensor information to estimate the correct orientation of the torso.

B. *Whole Body Coordination*

ASIMO's balance controller is based on the inverse pendulum model and is very stable. In this framework, the upper body is modeled simply as a mass and the dynamic model of the arm is not actively included to the balance controller. To achieve whole body control, the upper body controller and the lower body controller need to be connected. The communication between the upper body and the lower body is shown in Fig. 7.

In this framework, the effect of the arm motion needs to be affected to the balance controller as movement of center of the gravity points of both the arms. The information of the arm force sensor can also be affected to the balance controller. And desired position and orientation of the hip can be also sent to the balance controller. In the balance controller, actual hip command is calculated according to the desired command from upper body controller.

To calculate the upper body dynamics, the information of the actual hip position and orientation is necessary to compensate the gravity torque. It is very typical for the humanoid robot because the base of the arm moves according to the motion of the lower part. In this robot, gyro sensor is mounted on the body and is used to know the absolute orientation of the body. The sensor information is filtered and used for the balance controller. This filtered information is sent to the upper body dynamics control.

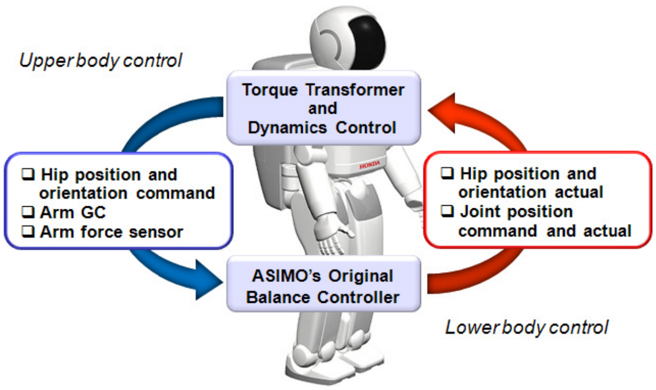


Fig. 7 Coordination between the upper body dynamics controller and the ZMP based HONDA ASIMO's balance controller. In this framework, (i) hip position and orientation command, (ii) arm GC and (iii) arm force sensor data are sent to the balance controller. (iv) The hip position and orientation actual and (v) the leg joint position command and actual are returned to the upper body dynamics control.

C. Hip Command

The hip has 6 DOF which is 3 DOF for position and 3 DOF for orientation. The movement of the hip is realized by the movement of the legs which has 6 DOF for each leg. In this framework, position and orientation of the hip can be commanded to the balance controller as a desired hip command. According to the desired command, the balance controller computes the internal command keeping the stable balance. In the balance controller, the hip position command is limited to keep the balance and the hip orientation control has higher priority than the hip horizontal position command.

In this framework, the hip command is decided according to the constraint function which is shown in Fig. 8.

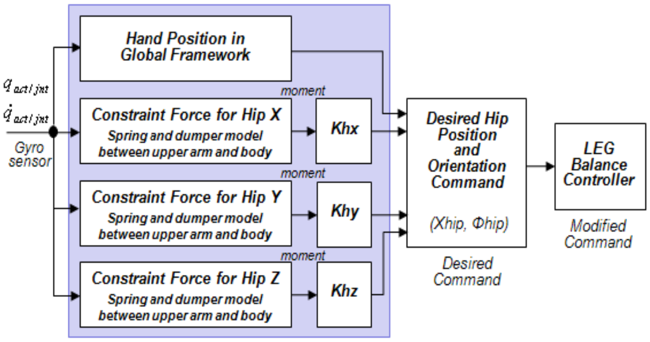


Fig. 8 Desired hip command. The hip height command and the hip orientation command of X, Y, and Z are decided according to the constraint forces between arms and the torso.

In the constraint function, the hip height command and the hip orientation command of X, Y, and Z are decided according to the constraint forces between arms and the torso, which are defined in Fig. 9. The distance between the arm and the torso is defined and the constraint forces are calculated according to the spring and dumper model. The constraint moments are calculated for the individual orientation command of the hip.

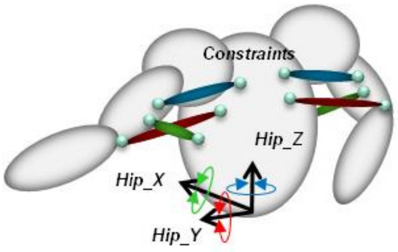


Fig. 9 Definition of the constraint forces for the individual hip orientation command. The hip X orientation is decided by constraint in blue. The hip Y orientation is decided by constraint in red. The hip Z orientation is decided by constraint in green.

D. Whole System

In Fig. 10, a block diagram of whole body motion controller is shown. In the motion controller, the Operational Space Formulation was applied to account for the dynamics of the system. The gravity vector in the dynamics of the system was compensated by the balance controller which computes the precise orientation using gyro sensor. The torque command from the motion controller is transformed into the velocity command to the motor control unit. The upper body dynamics is integrated and coordinated with the ZMP based balance controller of HONDA ASIMO. The desired hip position and the orientation are commanded from the constraint function.

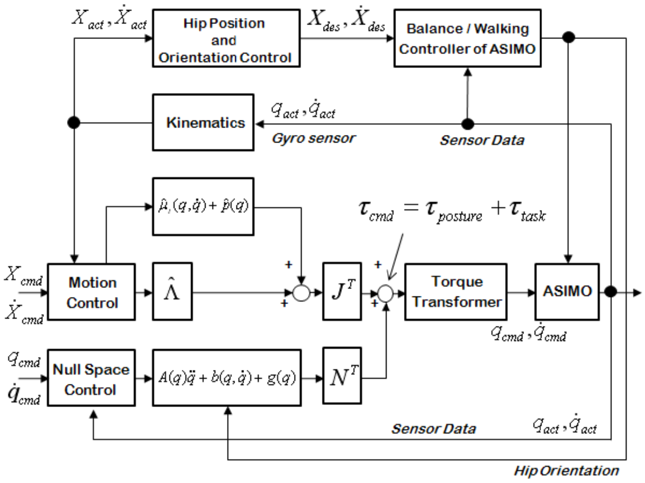


Fig. 10 A block diagram of whole body motion controller by (i) Torque Transformer, (ii) the Operational Space Formulation, (iii) Hip Controller and (iv) HONDA ASIMO's balance controller.

V. EXPERIMENTAL VALIDATION

A. Torque Transformer Test

In this test, gravity compensation torque was applied to the arms of ASIMO to see how Torque Transformer works correctly. Proposed torque transformer does not include a non-linear effect of a physical joint model between the motor and the output of the joint. If the joint friction in the physical joint is not negligible, its effect on the torque to position transformer is also not negligible. In case of the arm joints of ASIMO, the characteristics of the individual joint friction are different. The friction is mainly caused by Harmonic Drive gear, belt gear, mechanical hinge, etc. The effect of the friction also changes according to the mechanical condition. In this gravity torque test, the effect of the joint friction was ignored to see the pure effect of the torque transformer. Moreover, since the dynamics model of the upper body has 6 DOF for the base, the gravity vector of the upper body was compensated according to the movement of the body.

In the test, all the joints were manually and passively moved by an operator to see how the individual joints hold the connected link compensating the effect of the gravity. In Fig. 11, the blue line shows the torque command and the red line shows the resulting torque which was calculated by actual current data and torque constant Kt. In Fig. 11, the blue lines and the red lines are almost symmetry along the zero line even if the torso rotates. Through this test, the effect of the Torque Transformer was experimentally validated.

B. Operational Space Control Test

In this test, the Operational Space Command was applied to the position control of both hands in the Cartesian Space [9][13]. In Equation (15), $\dot{\vartheta}$ is defined as a simple PD control.

$$\dot{\vartheta} = f^* = K_{px}(x_{des} - x) + K_{vx}(\dot{x}_{des} - \dot{x}) \qquad (22)$$

K_{px} and K_{vx} are the space PD gains which are selected for the unit-mass system $\ddot{x} + K_{vx}\dot{x} + K_{px}x = 0$. The term x_{des} is a desired goal position. For a simple positioning task, the applied force to the task point is

$$F = \Lambda(x)(K_{px}(x_{des} - x) + K_{vx}(\dot{x}_{des} - \dot{x})) \qquad (23)$$

The joint torque corresponding to forces acting at the task is calculated by Equation (15).

The results of the experimental test are shown in Fig.12. In this test, sinusoid motion command was applied with the position gain K_{px} =1500 and the velocity gain, $K_{vx} = 2\zeta w_n = 2\zeta\sqrt{K_{px}}$ for the individual direction. In Fig. 12, the blue line is a desired position and the red line is an actual position in Cartesian space. When a position command was applied, the end-effecter followed the desired command with the position error under 0.005[m]. Through this test, it was verified that the accurate position control in Cartesian space can be achieved if position control is closed over the torque transformer.

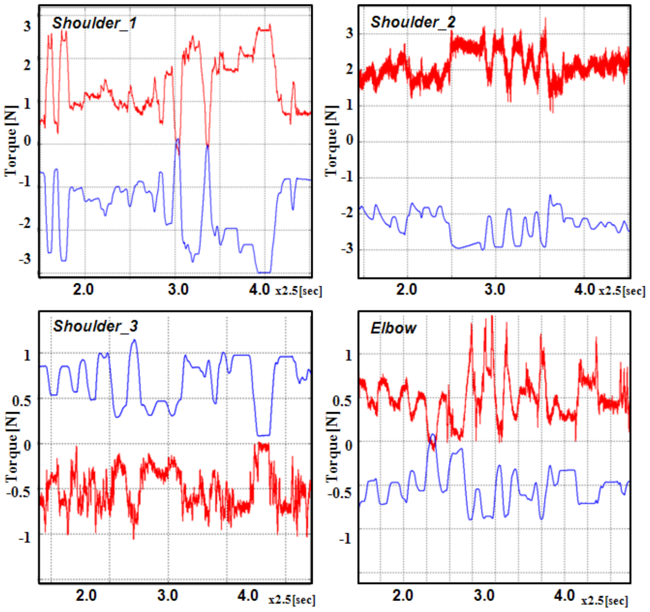


Fig. 11 Gravity torque compensation test of Torque Transformer. The transformer was applied to the both arms of HONDA ASIMO and gravity torque was sent to the transformer.

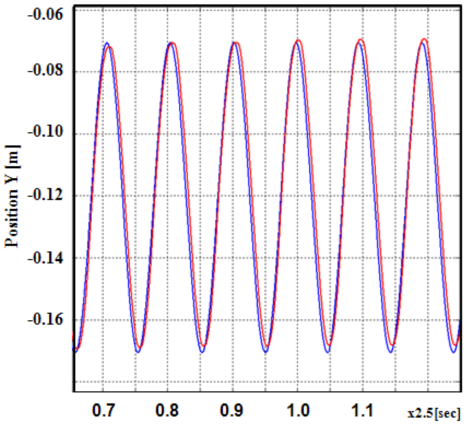


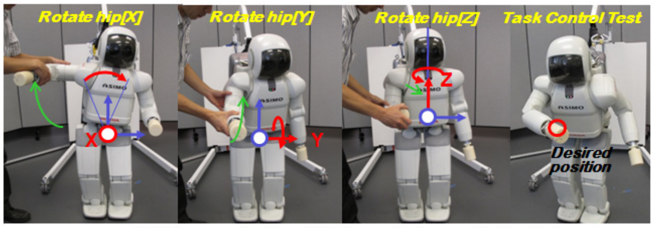
Fig. 12 The Operational Space Control on the Torque Transformer.

C. Whole Body Motion Control Test

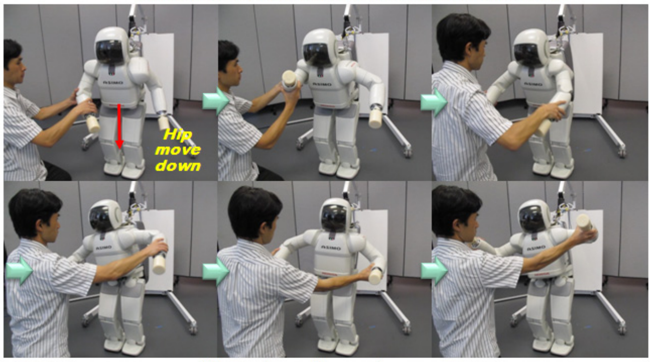
Fig. 13 shows the experimental result of physical interaction between ASIMO and human. Compliant and passive upper body torque control by the Torque Transformer and stable lower body control by the ASIMO's current balance controller were integrated together on the current position controlled system. The Operational Space Formulation was applied to the upper body motion control.

In Fig. 13(a), the upper body and the lower body coordination test is shown. According to the motion of the arms, the hip rotates along the X, Y and Z axis and moves up and down along the Z axis. Since the upper body and the lower body were coordinated, the lower body compensated the motion of the upper body and keeps the stable balance by the ASIMO's current balance controller. The task position control was also applied. If the hand was commanded to keep the desired position in global coordinate, which is defined as a middle point of both feet, the hand kept pointing the fixed position even if the torso moved. The robot also continued to keep pointing the commanded position even if the robot made several stamp walk.

In Fig. 13(b), continuous compliant interaction test with an operator is shown. In this test, only the gravity torque was commanded to the arms and the arms were passively operated by the operator. The operator could move the arms manually and the arms followed the operator's desired operation. The hip moved according to the motion of the arms to reduce the constraints between the arms and the torso. Through this test, flexible whole body motion control was realized. This framework is very important for safe and physical interaction between robots and human.



(a) The upper body and the lower body coordination test



(b) Continuous interaction test

Fig. 13 Whole body motion control test. Compliant and passive framework is achieved by the Torque Transformer. Stable balance control was achieved by the HONDA ASIMO's based balance controller. Upper body dynamics and the lower body balance controller were connected and coordinated together to realize the stable whole body motion control. The position and the orientation of the hip were commanded from the constraint function.

VI. CONCLUSIONS

i) New *Torque Transformer* was proposed. In this method, torque control is accomplished by converting desired joint torque into instantaneous increments of joint velocity command. *Torque Transformer* was defined and modeled precisely. Its availability was experimentally validated on ASIMO.

ii) The Operational Space Formulation was applied to the motion controller of ASIMO. Decoupled task dynamics was implemented on the upper body control. The torque command for all the joints were sent to the Torque Transformer and ASIMO's upper body was controlled.

iii) Compliant and passive upper body control by the Torque Transformer and stable lower body control by the HONDA ASIMO's balance controller were integrated together on the current position controlled robot.

iv) Flexible whole body motion control was realized. This framework is very important for safe and physical interaction between robots and human.

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