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EQUIVALENT INERTIA OF HUMAN-MACHINE SYSTEMS UNDER CONSTRAINT ENVIRONMENTS

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ABSTRACT

In this paper, we propose a new method to derive equivalent inertia of human-machine systems taking contact and constraint conditions into account. First, it is theoretically demonstrated that the inertia tensor in a generalized coordinate system of the human can be transformed, with Jacobian and contact constraint matrices, into any coordinate system on the object he/she is manipulating. Next, constraint inertia of the human-machine system is newly defined by using orthogonal complementary projection to the null space of the constraint conditions of the human and the object. Then, the equivalent inertia characteristics with respect to the steering angle in a 3-dimensional driver-steering-seat system are simulated under several contact and constraint conditions. The results give a significance of drivers steering strategy from a mechanical point of view, and a possibility to evaluate the human posture interacting the machine by using the equivalent inertia. Furthermore, response surfaces of the equivalent inertia are calculated with regard to layout parameters such as torso angle of the driver and inclination angle of the steering wheel, to investigate a possibility of the layout optimization.

1. INTRODUCTION

Almost all of the operations that human beings undertake, both they and the objects are constrained in a variety of ways. However, human beings actively utilize those constraints to alter the transmitting force between the human and the object. For example, when writing on a piece of paper, one can write small, complex characters quickly and precisely by placing the hand on the desktop. Also, when one brakes suddenly while driving a car, one is able to transmit greater force to the brake pedal by pressing one’s hips against the seat and utilizing the reaction force.

In research that analyzes the characteristics of human-machine systems, it is popular to model both the human and the machine using mechanical impedance, which consists of stiffness(Mussa-Ivaldi et al., 1985, Park and Sheridan, 2004), viscosity, and inertia (Tsuji et al., 1995, 1999, 2005). The inertial characteristics, in particular, are all determined by the posture and the environmental constraints, ignoring the effect of changing the shapes of the muscles. Therefore, by studying the equivalent inertia of human machine systems, it might be possible to clarify the physical significance of the skillful strategies of human beings.

In the field of robotics, on the other hand, Chiacchio et al. (1991) and Zheng et al. (1993) studied on the manipulability of multiple robot arms or multi fingered robot arm operating on a single object. Cutkosky and Kao (1989) and Jazidie et al.(1993) studied on methods of controlling the arms. In these studies, contact between the arms and the object is described by defining the directions in which force is transmitted and not transmitted at the point of contact. The same kind of methods can be used to describe contact between a human and an object, but in these studies, the constraints on the arms and the object are not taken into consideration. With this regard, Yoshikawa and Zheng (1993) and Jazidie et al.(1993) derived equation of motion of multiple robotic arms operating an object that is constrained by the external environment. These studies are, however, concerned with only control methods and little mentioned the effects of constraints on the inertia of the entire system.

This paper newly derives the equivalent inertia for a human-machine system that takes into consideration not only the contact between the human and the object, but also the constraints on the human and the object. First, it is theoretically demonstrated that the inertia tensors of the human and the object that are described in respective generalized coordinates can be transformed and synthesized into any coordinate on the object. Next, equation of motion and the constraint equations for the acceleration of the human and the object are used to define the equivalent inertia of the human-machine system taking into consideration the constraints imposed on both the human and the object. Then, the equivalent inertia characteristics with respect to the

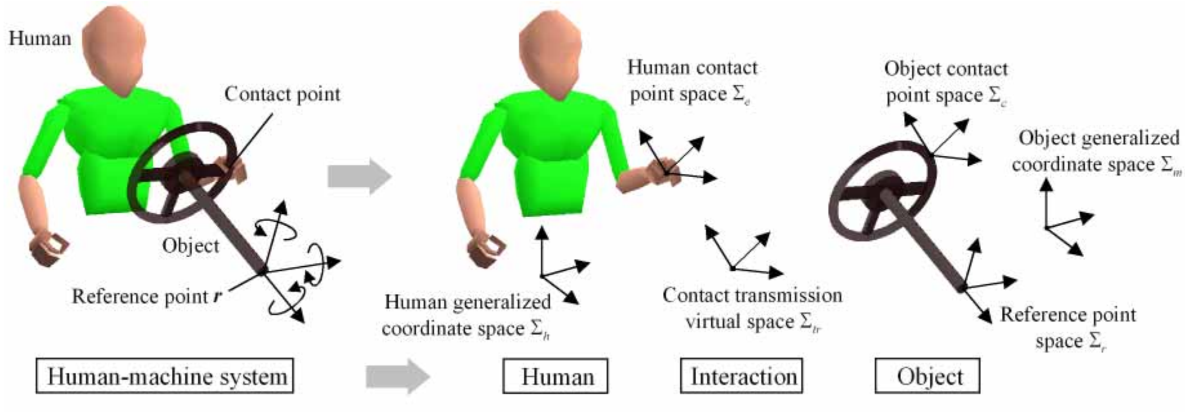


Figure 1 Example of human machine system with single contact point

Table 1 Contact constraint matrix in various contact conditions

Point contact	Knob grasping contact	Rigid contact
$H_1=\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\end{bmatrix}$	$H_1=\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&1&0&0\\0&0&0&0&1&0\end{bmatrix}$	$H_1=\begin{bmatrix}1&0&0&0&0&0\\0&1&0&0&0&0\\0&0&1&0&0&0\\0&0&0&1&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\end{bmatrix}$

steering angle in a 3-dimensional driver-steering-seat system are simulated under several contact and constraint conditions. Furthermore, response surfaces of the equivalent inertia are calculated with regard to layout parameters such as torso angle of the driver and inclination angle of the steering wheel, to investigate a possibility of the layout optimization.

2. EQUIVALENT INERTIA OF HUMAN-MACHINE SYSTEMS TAKING CONTACT INTO CONSIDERATION

2.1 Generalized Coordinates of the System

The human-machine system discussed in this paper, is treated as a single mechanical system that moves with interacting forces between the human and the object. Consider the case where the human-machine system is in a steady state. At this time, generalized coordinates of the system can be illustrated as shown in Figure 1. Σ_h is generalized coordinates that is composed of the vector $q_h \in R^n$, and that describes the human motion, while Σ_e is the coordinates for the human's contact with the object and is composed of the vector of the contact points $X_e \in R^{n_e}$.

Similarly, Σ_m is generalized coordinates that describes the movement of the object and is composed of the vector $q_m \in R^m$, while Σ_c is the coordinates for the object's contact with the human and is composed of the vector of the contact points $X_c \in R^{m_c}$. Σ_{tr} is virtual coordinates for the n_{tr} dimension that is used to describe the transmission of force at the contact points (Jazidie et al. 1993). While the human and the object are in contact, the three coordinates Σ_e, Σ_{tr} and Σ_c coincide, with their shared z axis oriented in the direction of a line normal to the plane of contact, and no shifting occurs in the contact point. Σ_r is the coordinates with its origin at r, the reference point for equivalent inertia, which can be defined at anywhere on the object. Note that the discussion in this paper is limited to the steady state for the sake of simplicity, but if generalized coordinates are configured in which the non-linear forces can be ignored, the discussion below also holds true for circumstances other than a steady state (Haug 1986).

Now supposing that both the human inertia tensor $M_h \in R^{n\times n}$ and the object inertia tensor $M_m \in R^{m\times m}$ are known in their respective coordinate frames Σ_h and Σ_m. Then the problem is how to derive the equivalent inertia tensor ${}^{hm}M_r \in R^{m_r\times m_r}$ of the human-machine system in the coordinate Σ_r. m_r is the degree of freedom of the point r, in the range $0 < m_r \le 6$. Also, neither the human nor the object is in a singular posture, so that $n \ge 6$, $n_e = m_c \ge n_{tr}$ and $m \ge 6$.

2.2 A Case of Single Contact Point

The first case to consider is when only a single point of contact exists between the human and the object, as illustrated in Figure 1. To make clear that contact exists at only one point, the subscript 1 is used as necessary.

At this time, using the Jacobian matrix $J_{e_1} \in R^{6\times n}$, following relationships as

$$\ddot{X}_{e_1} = J_{e_1}\ddot{q}_h , \quad (1)$$

$$\tau_h = J_{e_1}^T F_{e_1} \quad (2)$$

exist between Σ_h and Σ_e. Accordingly, M_h is transformed into Σ_e to obtain ${}^hM_{e_1} \in R^{6\times 6}$:

$$ {}^hM_{e_1} = (J_{e_1} M_h^{-1} J_{e_1}^T)^{-1} . \quad (3)$$

Next, the contact between the human and the object is expressed by the contact constraint matrix $H_1 \in R^{n_{tr1}\times 6}$ (Cutkosky and Kao 1989). This matrix dynamically indicates the direction in which force is applied to the object by the human, and kinematically indicates the direction in which constrained relative motion does not arise. For example, in the operation where the palm of the hand is pressed against the object (surface contact), H_1 becomes as follows,

$$H_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \quad (4)$$

This means that the contact force $F_{tr1} \in R^{n_{tr1}}$ that operates between the human and the object is translated into forces in three directions and into torque around the axis that is perpendicular to the plane of contact. Matrices for the other main contact conditions are shown in Table 1. ${}^hM_{e_1}$ in Σ_e is thus transformed into Σ_c as follows,

$$ {}^hM_{tr_1} = (H_1 {}^hM_{e_1}^{-1} H_1^T)^{-1} , \quad (5)$$

$$ {}^hM_{c_1} = H_1^T {}^hM_{tr_1} H_1 , \quad (6)$$

where ${}^hM_{tr_1}$ and ${}^hM_{c_1}$ are the equivalent inertia of the human, described in Σ_{tr} and Σ_c respectively.

With respect to the object, following relationships between Σ_c and Σ_m exist as is the case with (1) and (2).

$$\ddot{X}_{c_1} = J_{c_1}\ddot{q}_m , \quad (7)$$

$$\tau_m = J_{c_1}^T F_{c_1} , \quad (8)$$

where $J_{c_1} \in R^{m_{c1}\times m}$ is the Jacobian matrix. Accordingly,

$$ {}^hM_m = J_{c_1}^T {}^hM_{c_1} J_{c_1} \quad (9)$$

is obtained to transform ${}^hM_{c_1}$ into Σ_m, in which the inertia tensor of the object M_m is defined. Thus, ${}^hM_m$ and M_m can be added together, and applying the Jacobian matrix $J_r \in R^{6\times m}$ yields

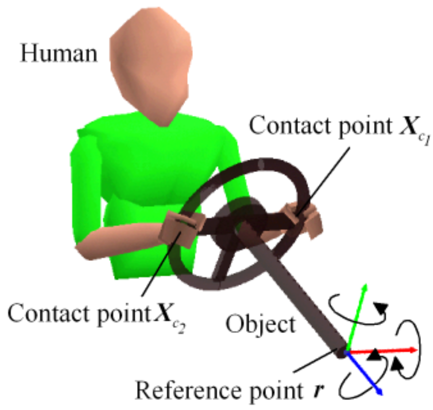


Figure 2 Example of human machine system with multiple contact points

$$ {}^{hm}M_r = (J_r {}^{hm}M_m^{-1} J_r^T)^{-1} , \quad (10)$$

$$ {}^{hm}M_m = {}^hM_m + M_m , \quad (11)$$

so that the equivalent inertia ${}^{hm}M_r$ of the human-machine system can be obtained for any point on the object. Note that because the mass is definitely positive, ${}^hM_m$ is positive definite. Therefore, for any nonzero value of $\ddot{x}_m \in R^m$, $\ddot{x}_m^{T\,h}M_m\ddot{x}_m \geq 0$ and $\ddot{x}_m^T M_m \ddot{x}_m > 0$ (Kodama 1978). At this time, the following inequality is to be true.

$$\begin{aligned} \ddot{x}_m^{T\,hm}M_m\ddot{x}_m &= \ddot{x}_m^T({}^hM_m + M_m)\ddot{x}_m \\ &= \ddot{x}_m^{T\,h}M_m\ddot{x}_m + \ddot{x}_m^T M_m \ddot{x}_m > 0 . \end{aligned} \quad (12)$$

2.3 A Case of Multi Contact Points

The next case to consider is when multiple k points of contact exist between the human and the object ($n_e = 6k$). Figure 2 shows an illustration of the case of $k = 2$.

At this time, the Jacobian matrix $J_e \in R^{n_e\times n}$, is defined with the Jacobian for each contact point J_{e_i}, $(i = 1, 2, ..., k)$ arranged vertically as follows:

$$J_e = \begin{bmatrix} J_{e_1} \\ J_{e_2} \\ \vdots \\ J_{e_k} \end{bmatrix} . \quad (13)$$

Similarly, the contact constraint matrix $H \in R^{n_{tr}\times n_e}$, $n_{tr} = \sum_{i=1}^{k} n_{tr_i}$, and the Jacobian matrix $J_c \in R^{m_c\times m}$ are defined by concatenating each matrix H_i and

J_{c_i} $(i=1,2,...,k)$ as follows:

$$H=\begin{bmatrix} H_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H_k \end{bmatrix}, \tag{14}$$

$$J_c=\begin{bmatrix} J_{c_1} \\ J_{c_2} \\ \vdots \\ J_{c_k} \end{bmatrix}. \tag{15}$$

In the same manner as with (3), (5), (6), (9) and (10), ${}^{hm}M_r$ can be derived by

$${}^{h}M_e=(J_e M_h^{-1} J_e^T)^{-1} \quad , \tag{16}$$

$${}^{h}M_{tr}=(H\,{}^{h}M_e^{-1} H^T)^{-1} \quad , \tag{17}$$

$${}^{h}M_c=H^T\,{}^{h}M_{tr} H \quad , \tag{18}$$

$${}^{h}M_m=J_c^T\,{}^{h}M_c J_c \quad , \tag{19}$$

$${}^{hm}M_r=(J_r\,{}^{hm}M_m^{-1} J_r^T)^{-1} \quad . \tag{20}$$

Note that ${}^{hm}M_m$ is given by (11). Therefore, except for over constrained case $(n_{tr}>n)$, the equivalent inertia ${}^{hm}M_r$ of a human-machine system can be obtained at any point r on the object, that takes the contact between the human and the object into consideration.

3. EQUIVALENT INERTIA TAKING CONSTRAINT INTO CONSIDERATION

This section considers the situation in which the human and the object are constrained as illustrated in Figure 3. First, a Jacobian matrix that takes the constraints on the human into consideration and the inertia are defined in the coordinate Σ_h. Next, the derivation of the equivalent inertia of a human-machine system that takes the constraints on the object into consideration is discussed. Note that only holonomic constraints that can be described by equalities are discussed in this paper.

3.1 Constraint Jacobian Matrix

The constraint on the human $\Phi_h \in R^{c_h}$ can be described as a function of q_h and time t, as follows:

$$\Phi_h(q_h,t)=0 \ . \tag{21}$$

Differentiating (21) with regard to time yields

$$G_h\,\dot{q}_h=-c \ , \tag{22}$$

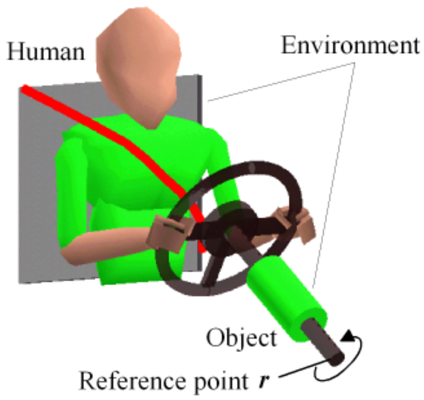


Figure 3 Example of human machine system where human and object are constrained

where $G_h=\partial\Phi_h/\partial q_h \in R^{c_h\times n}$ is the Jacobian matrix of constraint Φ_h and $c=\partial\Phi_h/\partial t \in R^{c_h}$. Equation (22) is then differentiated once more, the constraint equation for the acceleration is obtained (Haug 1986):

$$G_h\,\ddot{q}_h=-b_h \ , \tag{23}$$

$$b_h=\dot{G}_h\dot{q}_h+\dot{c} \ . \tag{24}$$

Except for cases where the human is completely constrained or over constrained, $rank(G_h)=c_h<n$. Therefore, solving (23) for $\ddot{q}_h$ yields

$$\ddot{q}_h=-G_h^+ b_h+P_h\eta \ , \tag{25}$$

for which there exist infinite number of solutions. G_h^+ is the pseudo-inverse matrix of G_h, and η is an arbitrary vector. Also, P_h is the matrix that describes the projection of G_h onto the null space $null(G_h)$, and it has the properties $P_h G_h^T=0$, $P_h^2=P_h$ and $P_h^T=P_h$ (Aghili and Piedbceuf, 2003). $null(G_h)$ can be regard as the sub space that is made up of admissible degrees of freedom of the human against constraint Φ_h. Therefore, it is possible to define the constrained Jacobian that accounts for the constraint on the human (Nenchev, 1992),

$$\bar{J}_e=J_e P_h \ . \tag{26}$$

3.2 Constraint Inertia

The equation of motion for the human who is in contact with the object and is constrained by the external environment can be described as follows:

$$M_h\ddot{q}_h+h_h(q_h,\dot{q}_h)+G_h^T F_{\phi_h}=\tau_h-J_e^T F_{e_m} \quad , \tag{27}$$

where $h_h(q_h, \dot{q}_h) \in R^n$ is the gravity term plus the centrifugal force and Coliolis force. $F_{\phi_h} \in R^{c_h}$ is the constraint force resulting from Φ_h, and $\tau_h \in R^n$ is the joint torque that is generated in the joints by the muscles. $F_{e_m} = H^T HF_c \in R^{n_e}$ is the contact force that is transmitted from the object. If both sides of (25) are multiplied from left by the matrix $(I_n - P_h)$, which describes the projection onto the orthogonal complementary space of $null(G_h)$, then as long as $P_h^2 = P_h$, the following is obtained (Aghili and Piedbceuf, 2003).

$$(I - P_h)\, \ddot{q}_h = G_h^+ b_h \quad , \tag{28}$$

where $I_n \in R^{n\times n}$ is the unit matrix. Here, if both sides of (28) are multiplied from the left by M_h, and both sides of (27) are multiplied from the left by P_h, and the results are added together, then if care is taken so that $P_h G_h^T = 0$, we have

$$M'_h \ddot{q}_h = P_h d_h - M_h G_h^+ b_h \quad , \tag{29}$$

$$M'_h = M_h + \overline{M}_h \quad , \tag{30}$$

$$\overline{M}_h = P_h M_h - (P_h M_h)^T \quad , \tag{31}$$

$$d_h = \tau_h - h_h(q_h, \dot{q}_h) - J_e^T F_{e_m} \quad . \tag{32}$$

Here, $M'_h \in R^{n\times n}$ is the constrained inertia that takes the constraint on the human into consideration. Note that because $\overline{M}_h^T = -\overline{M}_h$, $\overline{M}_h \in R^{n\times n}$ becomes the skew symmetric matrix. For that reason, for any nonzero , the following equality is to be true.

$$\begin{aligned} \ddot{x}_h^T \overline{M}_h \ddot{x}_h &= \ddot{x}_h^T (P_h M_h \ddot{x}_h) - (P_h M_h \ddot{x}_h)^T \ddot{x}_h \\ &= 0. \end{aligned} \tag{33}$$

Therefore, according to (30), we get

$$\ddot{x}_h^T M'_h \ddot{x}_h = \ddot{x}_h^T M_h \ddot{x}_h . \tag{34}$$

So when M_h is positive definite, M'_h is always positive definite (Aghili and Piedbceuf, 2003).

3.3 Constraint Equivalent Inertia

In the same manner as was done with (16), (17), (18) and (19) to become the equivalent inertia, which is transformed into the coordinate ,

$${}^h M'_e = (\bar{J}_e M_h'^{-1} \bar{J}_e^T)^{-1} \quad , \tag{35}$$

$${}^h M'_m = J_c^T H^T (H\ {}^h M_e'^{-1} H)^{-1} H J_c \quad . \tag{36}$$

The constraint on the object can also be handled in the same way that was discussed in the preceding section. Using the Jacobian matrix $G_m \in R^{c_m \times m}$, which is related to the constraint $\Phi_m \in R^{c_m}$ that is described in Σ_m, as well as the matrix P_m, which describes the projection of onto the null space, and the constrained Jacobian matrix $\bar{J}_r$, we have

$$\bar{J}_r = J_r P_m \quad , \tag{37}$$

$${}^{hm}M''_m = {}^{hm}M'_m + {}^{hm}\overline{M}'_m \quad , \tag{38}$$

$${}^{hm}\overline{M}'_m = P_m\, {}^{hm}M'_m - (P_m\, {}^{hm}M'_m)^T \quad , \tag{39}$$

$${}^{hm}M'_m = {}^h M'_m + M_m \quad . \tag{40}$$

Therefore, the equivalent inertia of the human-machine system that takes the constraint on both the human and the object can be expressed by

$${}^{hm}M''_r = (\bar{J}_r\, {}^{hm}M_m''^{-1} \bar{J}_r^T)^{-1} \tag{41}$$

in the same manner as in (20).

The discussion up to this point has defined the equivalent inertia ${}^{hm}M''_r$ of the human-machine system in accordance with the degree of freedom at any given point on the object, taking into account not only the various forms of contact between the human and the object, but also the constraints on the human and the object.

4. NUMERICAL EXAMPLES

In order to clarify the significance of the equivalent inertia of the human-machine system that takes constraint into consideration, the calculations described below were carried out.

4.1 Equivalent Inertia of a Driver-Steering-Seat System

The effect on equivalent inertia of the combination of constraints on the human and contact between the human and the object were studied using a driver-steering-seat system shown in Figure 4.

The driver was modeled as articulated rigid bodies in which the shoulder and wrist joints were treated as spherical joints with 3 degrees of freedom, while the elbow was treated as a cylindrical joint with 1 degree of freedom. The entire system, including the torso, had a total of 20 degrees of freedom. The dimensions of the arms and their inertial parameters were set as shown in Table 2.

In order to clarify the effects of characteristics of the human, the inertia values for both the steering and the seat were set to zero. The hip point and shoulder points, which define the human, were set in advance to the values shown in Table 3.

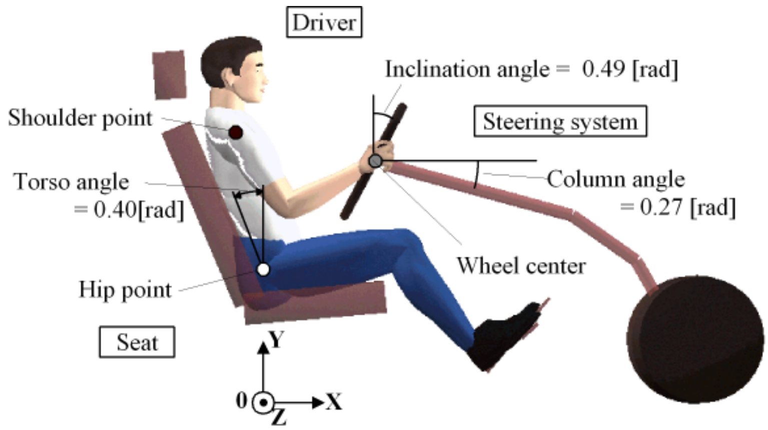


Figure 4 Driver-steering-seat system

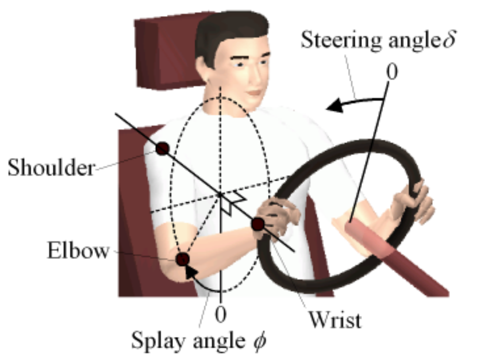


Figure 5 Steering angle and splay angle

Table 2 Inertia properties of human arm

(x 10^{-3}kgm^2)

	I_{xx}	I_{yy}	I_{zz}
Upper arm	7.22	0.93	7.28
Forearm	3.99	0.73	3.76
Hand	0.17	0.04	0.51

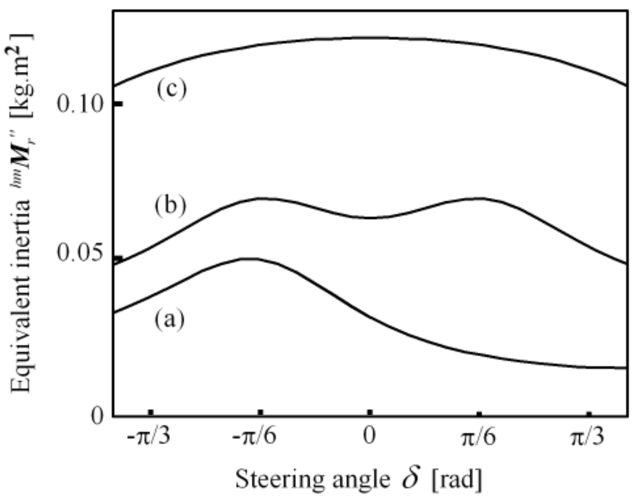


Figure 6 Equivalent inertia characteristics in relation to steering angle of driver-steering-seat system

Table 3 Positions of hip, shoulder and steering wheel

	x (m)	y (m)	z(m)
Hip point	0.000	0.302	0.000
Shoulder point (right)	-0.104	0.437	0.189
Shoulder point (left)	-0.104	0.437	-0.189
Center of steering wheel	0.302	0.662	0.000

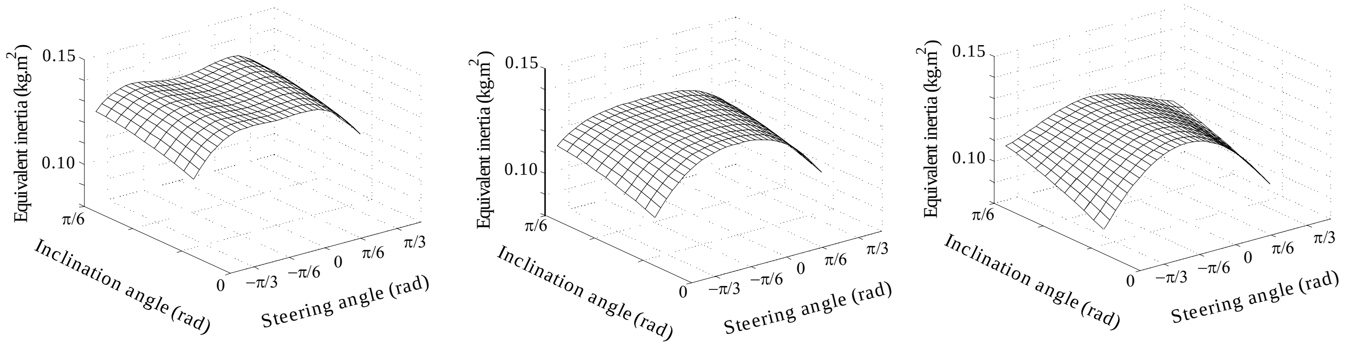
The driver's torso was defined as completely constrained by the seat and seat belt, and three conditions were defined:

(a) the palm of the driver's right hand touching the steering wheel (surface contact),
(b) both hands gripping the wheel (rigid contact), and
(c) both hands gripping the wheel (rigid contact) with both wrists constrained.

Changing the steering angle δ, the equivalent inertia ${}^{hm}M_r^{''} \in R^1$ around the axis of rotation of the steering column was then calculated for each set of conditions. The steering angle δ was defined to be zero when the vehicle is moving straight forward, with rotation to the right defined as positive. It is supposed that, when $\delta = 0$, the driver's right hand is at the 3 o'clock position, with the left hand at the 9 o'clock position when the driver grips the wheel with both hands, and these positions does not change during steering.

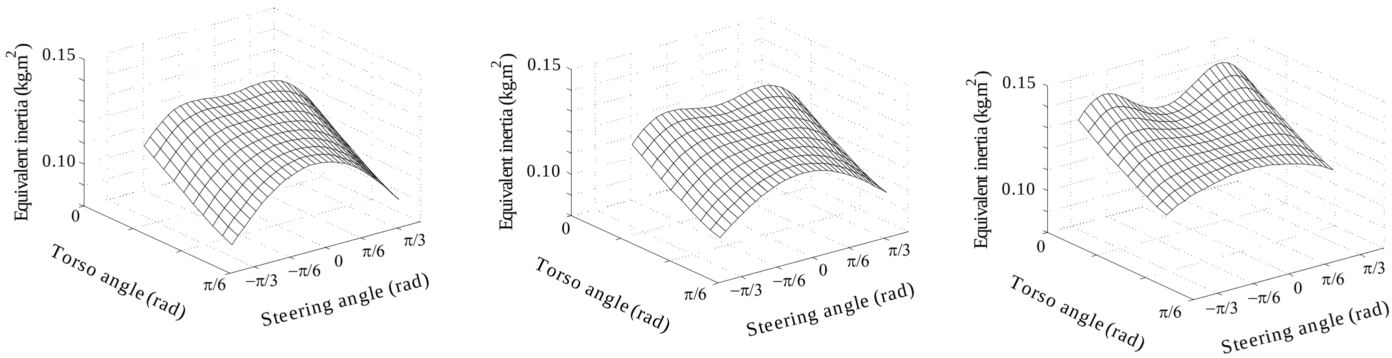
Also, because the arms have redundant degrees of freedom, their orientation cannot be uniquely determined by the steering contact conditions alone. Accordingly, referring to the research on driving postures by Schneider (1999), the splay angle ϕ, which defines the angle of opening of the elbow, was set to a constant 0.15 [rad] as shown in Figure 5. The method of Tolani et al.(2000), was then used to determine the orientation of the arms uniquely.

Figure 6 shows the calculated results for the three sets of conditions. The horizontal axis is the steering angle, and the vertical axis is the equivalent inertia of the human-machine system. For the condition (a), the inertia shows asymmetrical changes between left and right and reaches its maximum value around $-\pi/6$. By contrast, for the condition (b), the changes are nearly symmetrical between left and right, and the values are higher than for the condition (a), but the amount of change in relation to the steering is less. The results for the condition (c) show the same general pattern as for (b), but with a shift from two peaks to just one. These results indicate that because the driver does more steering for (b) than for (a), and more for (c) than for (b), the equivalent



(a) Torso angle 0.21 rad　(b) Torso angle 0.35 rad　(c) Torso angle 0.49 rad

Figure 7 Equivalent inertia characteristics in relation to inclination angles for different torso angles



(a) Inclination angle 0.21 rad　(b) Inclination angle 0.49 rad　(c) Inclination angle 0.70 rad

Figure 8 Equivalent inertia characteristics in relation to torso angles for different inclination angles

inertia around the axis of rotation of the steering column increases accordingly. Moreover, at the same time that the driver is increasingly sensitive to the acceleration that is transmitted from the road surface, the changes in inertia in the driver's own body during steering are reduced, which is thought to make it easier to feel the effects of inertial changes in the object (the automobile) that occur as a result of the changes in the geometry of the suspension and the tires.

As mentioned above, using the equivalent inertia of the human-machine system thus makes it possible to observe the physical significance of operations that human beings perform routinely.

4.2 Response Surfaces of Equivalent Inertia

According to the discussion in the preceding section, it is considered good to make the equivalent inertia during steering as large as possible and to reduce its changes in relation to the steering angle. The torso angle and inclination angle shown in Figure 4 were therefore treated as design variables, and the equivalent inertia ${}^{hm}M_r''$ was calculated under the conditions for case (c) in the preceding section.

Figure 7 shows the changes in the equivalent inertia in relation to the inclination angle and steering angle for three different settings of the torso angle. Similarly, Figure 8 shows the changes in the equivalent inertia in relation to the torso angle and steering angle for three different settings of the inclination angle. The equivalent inertia decreases as the torso angle increases, and its changes in relation to the steering angle shift from two peaks to one. By contrast, the equivalent inertia increases as the inclination angle increases, and its changes in relation to the steering angle divide into two regions, one where the changes shift from one peak to two, and another where the single peak remains, but the changes become smaller. It can also be seen that between the two regions there exists a region in which there is almost no change in the equivalent inertia.

To provide more detailed understandings, further analyses are needed to incorporate the position of the steering wheel in relation to the driver, both longitudinally and vertically, but these results strongly suggest that optimum values for the torso angle and inclination angle can be obtained by establishing evaluation functions that use the equivalent inertia of the human-machine system.

5. CONCLUSIONS

In this paper, a new method of deriving the equivalent inertia of a human-machine system has been described that takes into consideration not only the contact between the human and the object, but also the constraints on the human and the object. In addition, the usefulness of the method has been shown through the simulations of driver-steering-seat systems. Specifically, the following points have been demonstrated:

1) Inertia tensors for the human and the object that are defined in generalized coordinates can be transformed into any given coordinate on the object and synthesized by using Jacobian matrices and contact constraint matrices.
2) The equivalent inertia of a human-machine system that takes constraint into consideration can be defined by using the equations of motion and acceleration constraint expressions for the human and the object, also by focusing on the complimentary orthogonality between the range and null space.
3) The equivalent inertia of the human-machine system makes it possible to observe the physical significance of the driver's operations in a driver-steering-seat system, and it can be utilized as an index in evaluating the driver's posture.

The equivalent inertia that is proposed in this paper can be used to study how the human can utilize his/her own posture and constraints according to the nature and purpose of the operation and in what manner the control characteristics of the human-machine system can be adjusted. Note that this paper deals only with holonomic constraints. Henceforth, it will be necessary to extend this theory so that it can handle non-equality constraint conditions and non-holonomic constraint conditions and to consider methods of expressing the equivalent inertia of a human-machine system so that it will be easy to understand in a three-dimensional space. It is hoped that combining these methods with optimization techniques will lead to the development of specific methods for designing the equivalent inertia of human-machine systems. Moreover, expanding the analysis to include the equivalent impedance of human-machine systems, taking into consideration not only inertia, but also viscoelasticity, could make it a useful tool for considering new strategies in the design of control and hardware in human-machine systems.

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