Development and Control of Multi-Degree-of-Freedom Mobile Robot for Acquisition of Road Environmental Modes

Naoya Murata  Student Member  (Keio University, murata@katsura.sd.keio.ac.jp)
Seiichiro Katsura  Senior Member  (Keio University, katsura@sd.keio.ac.jp)

**Keywords:** motion control, real-world haptics, disturbance observer, modal decomposition, mobile robot, acceleration control

Acquisition of information about the environment around a mobile robot is important for purposes such as controlling the robot from a remote location and in situations such as when the robot is running autonomously. In many researches, audiovisual information is used. However, acquisition of information about force sensation, which is included in environmental information, has not been well researched. The mobile-hapto, which is a remote control system with force information, has been proposed, but the robot used for the system can acquire only the horizontal component of forces. For this reason, a “multi-degree-of-freedom mobile robot” has been developed in this study. It is a three-wheeled mobile robot. Fig. 1 shows a photograph of the robot. It has direct drive rotary motors for each wheel and at the steering section. There are linear motors between the body and each wheel. By using these motors, the robot can get information on the position (degree) and force (torque) in the horizontal and vertical directions. The force (torque) information is obtained by a reaction force (torque) observer without force sensors. By using this robot, detailed information on the forces in the environment can be acquired, and the operability of the robot and its capability to adjust to the environment are expected to improve.

In this study, modal decomposition is used to extract information on the road surface and the state of the robot. Coordinate transformation of information in the motor space to that in the modal space is performed. The information acquired by the rotary motors is transformed into the translational mode, yawing mode, and elastic mode. The information acquired by the linear motors is transformed into the heaving mode, rolling mode, and pitching mode. Figs. 2 and 3 show the modes used for modal decomposition. $z_F$, $z_R$, and $z_L$ denote information acquired by the front, right, and left motors.

In the experiment performed in this study, the robot traveled over three obstacles, with its height being controlled by the linear motors. Fig. 4 shows the positions of obstacles and the default position of the robot. Fig. 5 shows torque responses acquired by rotary motors in the modal space. Fig. 6 shows force responses acquired by linear motors in the modal space. In these figures, the difference between the instant when front wheel travels over an obstacle and that when the rear wheel travels over the obstacle can be determined. Further, the difference between the right and left wheels can also be seen. This experiment confirmed the capability of the robot to obtain road surface information.
Electric Vehicle Range Extension Control System Based on Front- and Rear-wheel Sideslip Angle and Left- and Right-motor Torque Distribution

Hayato Sumiya  Student Member (The University of Tokyo, sumiya@hflab.k.u-tokyo.ac.jp)
Hiroshi Fujimoto  Senior Member (The University of Tokyo, fujimoto@k.u-tokyo.ac.jp)

Keywords: electric vehicle, front active steering, driving and braking force distribution, range extension control system

Nowadays, electric vehicles (EVs) are attracting considerable attention. EVs have some features because of which they do not cause environmental problems. In addition, EVs driven by electric motors have four advantages. First, the use of in-wheel motors enables individual control of each wheel. Second, continuous and smooth braking torque can be generated by regeneration. Third, the generated torque can be precisely measured from the motor current. Finally, quick torque response is possible by motor current control. These advantages enable effective vehicle motion control.

EVs are not widely used because of some problems. The mileage per charge is the most critical issue in the use of EVs. EVs have a battery as the driving source. Therefore, the mileage per charge depends on the battery capacity. High efficiency motors have been developed in many studies to solve this problem. However, in order to solve this problem effectively, the battery capacity needs to be improved.

In this paper, the range extension control system (RECS) is proposed to solve the problem of mileage per charge for effective vehicle motion control. We assume that EVs have an active front steering unit and motors in left and right wheels. When a conventional vehicle is running on a curving road, a yaw moment is generated by the front steering angle only. However, the front steering angle also generates cornering resistance. We propose a method in which a yaw moment is generated by the front steering angle because of the difference in the diving force between the left and right motors. The front steering angle considered in the proposed method can be smaller than that considered in the conventional method. This enables a reduction in the cornering resistance. Thus, the mileage per charge is improved.

Fig. 1 shows the block diagram of the RECS. Fig. 2 shows the experimental results. Front steering angle is reduced by proposed method and yaw-moment generated by torque difference between left and right motors are occurred as shown in Fig. 2(a) and Fig. 2(b). Fig. 2(c) shows the vehicle trajectory. The vehicle trajectories corresponding to both methods are the same. Fig. 2(d) shows the power loss. The power loss in the case of the proposed method is lower by almost 50 W than that in the case of the conventional method. Table 1 shows the mileage per charge. It can be increased to about 200 m/kWh by using this method.

Fig. 1. Block diagram of range extension control system

Fig. 2. Experimental results

Table 1. Mileage per charge

<table>
<thead>
<tr>
<th>Battery capacity</th>
<th>Without RECS</th>
<th>With RECS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kWh</td>
<td>8.03 km</td>
<td>8.20 km</td>
</tr>
<tr>
<td>16 kWh</td>
<td>128.61 km</td>
<td>131.23 km</td>
</tr>
</tbody>
</table>
Tele-Operation of a Mobile Haptic System Using Dynamical Modal Transformation

Wataru Yamanouchi  Student Member (Keio University, babel@katsura.sd.keio.ac.jp)
Seiichiro Katsura  Senior Member (Keio University, katsura@sd.keio.ac.jp)

Keywords: motion control, real-world haptics, bilateral control, mobile robot, acceleration control, modal transformation

Recent advances in control technology have contributed to the development of robot systems for communication. Robot systems recognize their environment on the basis of audio-visual information. Recognition methods based on audio-visual feedback have been developed by many researchers. Apart from auditory and visual information, haptic information has recently attracted attention as the third type of multimedia information. The sense of touch is useful for remote manipulation.

Feedback of haptic information is realized by bilateral control. In conventional research, most systems are constructed using a master-slave system in which the master-slave systems have the same mechanical structure. However, very few studies have been carried out on force feedback systems with different mechanical structures. This paper proposes a novel control method for mobile-hapto, which involves force feedback using mobility systems. The concept of the mobile-hapto is shown in Fig. 1.

In this study, the mobile-hapto consists of a mobile robot that can move in an infinite area for motion and a joystick that is fixed at a given position and can be operated manually. To realize of force feedback in the mobile-hapto, a modal transformation matrix for bilateral control is proposed. The proposed modal transformation matrix is defined as

\[ D_2 = \begin{bmatrix} 1 & A \\ C & D \end{bmatrix}. \]  

(1)

The coefficients of the matrix are defined as

\[ A = 1 \]  

(2)

\[ B = 1 \]  

(3)

\[ C = 1 \]  

(4)

\[ D = \frac{s g_{fd}}{s + g_{fd}} \begin{bmatrix} s g_{acc} \end{bmatrix} \]  

(5)

where \( g_{fd} \) and \( g_{acc} \) are the cut-off frequencies of the low pass filters. The coefficient D is the second-order pseudo-differential. The proposed matrix is able to change the dimension of the controlled value.

The joystick is treated as a pedal by changing two dimensions of the mobile robot position.

Figs. 2 and 3 show the experimental results of the translational mode. The joystick operates as an acceleration pedal of the mobile robot. The operation is carried out on a flat area, on a grass area and in conditions where the robot can come in contact with a wall. The law of action and reaction is artificially generated in the remote environment between the mobile robot and the joystick. The position of the joystick is synchronized with the acceleration of the mobile robot. Thus, the mobile-hapto based on bilateral control using the proposed modal transformation matrix can possibly be subjected to intuitive manipulation.
Fine-Motion-Control Method for Realizing High-Accuracy and High-Speed Contact Motion of Industrial Robots by Employing Sensorless Force Control

Naoki Shimada Student Member (Nagaoka University of Technology, shimayan@stn.nagaokaut.ac.jp)
Takashi Yoshioka Student Member (Nagaoka University of Technology, marui29@stn.nagaokaut.ac.jp)
Kiyoshi Ohishi Senior Member (Nagaoka University of Technology, ohishi@vos.nagaokaut.ac.jp)
Toshimasa Miyazaki Member (Nagaoka University of Technology, miyazaki@vos.nagaokaut.ac.jp)

Keywords: force control, industrial robot, disturbance observer

Although industrial robots have become considerably important in the modern industrial society, their functions are limited. A typical limited function is the positioning motion control of necessary for robots used in the manufacturing industry. In contrast, contact motion is applicable to almost all new robot applications. In this paper, we propose a new smooth-contact-motion method to be used in tracer control based on sensorless force control of industrial robots.

First, the jerk signal based on an estimated force enables the rapid detection of contact. The jerk signal is a derivative value of the estimated force, as given by Eq. (1).

\[ G_f = \frac{dF}{dt} \]  

(1)

The external-force estimation is somewhat erroneous because of dynamics compensation. Such a compensation is required as it is difficult to estimate the precise values of inertia and friction. For these reasons, the distinction between the free-motion and the contact-motion is unclear in the case of the estimated external force. The conventional method for detecting contact using the threshold of the external force is not fast. In contrast, using the proposed method is very rapid, as it is detection based on the jerk signal.

Dynamic braking effective decreases the dynamic energy. Such braking occurs immediately after the robot comes in contact with an object, that is maximum torque control of all robot joints. Moreover, the torque control is continued until each joint’s energy is cancelled out completely. The motion can be expressed by Eq. (2).

\[
\begin{align*}
I_{\text{brake}}[n] &= \begin{cases} 
\text{sign}(\omega_{L}[n])K_{\text{frC}}[n]|l_{\text{limit}}[n]| & : W_{\text{imp}}[n] > (W_{\text{brake}}[n] + W_{\text{en}}[n]) \\
0 & : W_{\text{imp}}[n] \leq (W_{\text{brake}}[n] + W_{\text{en}}[n])
\end{cases}
\end{align*}
\]  

(2)

The integrator of the I-P (Integral-Proportional) force control is initialized with the optimal initial value for the contact motion of industrial robots. The initial value is calculated using Eq. (3). This operation restricts the unwanted motion caused by an impulsive force.

\[ W_{\text{int}} = \frac{(F_{\max} - F_{\text{rel}})K_{\text{frC}} + (\theta_{\max} - \theta_{0})K_{\text{frC}}}{2} \]  

(3)

The validity of the proposed method is confirmed by the contact motion experiment illustrated in Fig. 1. A three-degree-of-freedom robot is brought into contact with the upper end of the environment. The contact speed is 250 mm/s in this experiment. The robot comes into contact with a concrete block after a long time (\(\approx 4\) s), as shown in Fig. 2. Further, from Fig. 3, which shows the results obtained using the proposed method, the validity of the proposed method is confirmed. By employing the proposed method, smooth-contact-motion control of industrial robots for some advanced applications is achieved.
Control of Thermal Conductance of Peltier Device Using Heat Disturbance Observer

Hidetaka Morimitsu  Student Member  (Keio University, mori@katsura.sd.keio.ac.jp)
Seiichiro Katsura  Senior Member  (Keio University, katsura@sd.keio.ac.jp)

Keywords: Peltier device, thermal control, disturbance observer, thermal conductance

Temperature control and heat flow control are carried out in industries for many thermal devices, including the Peltier device, which facilitates heat transfer by electric current. Temperature control generally compensates for the heat flow from the external environment, while the heat actively flows into the system during heat flow control. This is the main difference between temperature control and heat flow control. In this paper, thermal conductance of control is defined as shown in (1) to describe the characteristics of thermal control.

\[
\frac{\partial q}{\partial T} = \gamma \tag{1}
\]

\(T\), \(q\), and \(\gamma\) denote the system temperature, heat flow from the external environment, and the thermal conductance of control, respectively. In the case of ideal temperature control, the \(T\) does not change even when \(q\) flows into the thermal system, implying that \(\gamma = \infty\). In contrast, in the case of ideal heat flow control, heat flow \(q\) does not vary even when \(T\) changes, and \(\gamma\) becomes 0.

In the past, a thermal control process in which \(\gamma\) is between 0 and \(\infty\) has not been discussed in detail. Therefore, this study focuses on \(\gamma\) and the construction of a thermal conductance control system for a Peltier device using a heat disturbance observer. In this system, a thermal conductance controller is implemented, and control that is thermally compliant with the external environment is conducted.

The thermal conductance control is illustrated in Fig. 1. \(R\), \(C\), and \(G\) stand for thermal resistance, thermal capacitance, and thermal conductance \(G = 1/R\), respectively. The subscripts \(o\), \(sen\), \(v\) denote object, thermal sensor, and variable (which is set virtually), respectively. \(q^o\) and the superscript \(ref\) indicate heat inflow and a reference value, respectively. In the case of ideal temperature control without the thermal conductance controller, the reference temperature \(T_{ref}\) corresponds to the sensor temperature \(T_{sen}\), and the control system compensates for heat inflow \(q^o\) as a disturbance. On the other hand, \(T_{sen}\) differs from \(T_{ref}\) when the thermal conductance controller is implemented. In this control system, \(T_{sen}\) changes with \(q^o\), and \(\gamma\) becomes lower than \(\infty\). The variation of \(\gamma\) is decided by the value of the thermal conductance \(G\), which can be set arbitrarily. As a result, control in which \(\gamma\) is between 0 and \(\infty\) is realized. Factors such as parameter identification error are compensated for by the heat disturbance observer, and the thermal control itself is conducted with sufficient robustness.

Experiments are conducted for several values of \(G\). The temperature and heat inflow responses are shown in Figs. 2 and 3. In the experiments, \(T_{ref}\) is set at 15°C, and \(q^o\) is generated by contact of the thermal system with an aluminum block at 15 seconds. When \(G\) is \(\infty\), the heat inflow is fully compensated for, and \(T_{sen}\) corresponds to \(T_{ref}\) again. However, when \(G\) is less than \(\infty\), \(T_{sen}\) changes with \(q^o\) and \(G\). From this observation, it is concluded that control that is thermally compliant with \(q^o\) is realized. The proposed system considers the relationship between the thermal system and the external environment, and it is expected to have applications in thermal control engineering.
Stiffness Ellipse Control of Tendon Mechanisms with Nonlinear Springs

Fumihiro Okumura Non-member (Mie University, okumura@ems.elec.mie-u.ac.jp)
Satoshi Komada Member (Mie University, komada@elec.mie-u.ac.jp)
Junji Hirai Member (Mie University, hirai@elec.mie-u.ac.jp)

Keywords: nonlinear springs, tendon mechanisms, stiffness ellipse control

Versatile and safe manipulators are required for use in human environments. A tendon mechanism with nonlinear springs is one candidate that can satisfy the requirements of versatility and safety. In the tendon mechanism, mechanical stiffness is controlled at the joint coordinates and not at the ends of arms that perform the tasks. This study shows the transformation of the stiffness ellipse at the ends of arms to joint stiffness. The derived transformation is applied to both mechanical stiffness and control stiffness; the control system is called the hybrid stiffness ellipse control.

The stiffness ellipse at the ends of arms shown in Fig. 1 is represented by three parameters: the short axis $A$, long axis $B$, and rotation direction $\phi$. The algorithm for deriving the joint stiffness $S_j$ that achieves the stiffness ellipse is shown below.

- Arm end stiffness $S_w$ is derived from the stiffness ellipse as follows:

$$S_{w11} = A \cos^2\phi + B \sin^2\phi$$
$$S_{w12} = (A - B) \sin\phi \cos\phi$$
$$S_{w22} = A \sin^2\phi + B \cos^2\phi$$

(1)

- $S_w$ is transformed into $S_j$ as follows:

$$S_j = J(q)^T S_w J(q)$$

(2)

The hybrid stiffness ellipse control system, as shown in Fig. 2, where the transformation is applied to both mechanical joint stiffness and controller gain of joint angle controller is proposed.

The effectiveness of the mechanical stiffness ellipse control, the control stiffness ellipse control, and the hybrid stiffness ellipse control is verified by simulation results. Each function of the mechanical stiffness and control stiffness is revealed. The control object is the tendon mechanism with three pairs of six muscles with biarticular muscles with tendons. Fig. 3 shows the transient response of the end of the arm to a step external force when mechanical stiffness ellipse commands ML and MH, and control stiffness ellipse commands CL and CH are applied at that end. Here, L and H represent low stiffness and high stiffness, respectively. By comparing $\alpha$ and $\beta$, the effect of mechanical stiffness can be understood. By comparing $\alpha$ and $\gamma$, effect of control stiffness can also be understood. Since the steady-state deviations of $\alpha$ and $\beta$ are the same, only the control stiffness influences the steady state deviation. Since the initial responses of $\alpha$ and $\gamma$ are the same, only mechanical stiffness influences the initial response. Therefore, the mechanical stiffness and the control stiffness are dominant initially and finally, respectively.
Control System for Suppressing Tracking Error Offset and Multiharmonic Disturbance in High-Speed Optical Disk Systems

Yuta Nabata  Student Member (Nagaoka University of Technology)
Tatsuya Nakazaki  Student Member (Nagaoka University of Technology)
Tokoku Ogata  Student Member (Nagaoka University of Technology)
Kiyoshi Ohishi  Senior Member (Nagaoka University of Technology)
Toshimasa Miyazaki  Member (Nagaoka University of Technology)
Masaki Sazawa  Member (Nagaoka University of Technology)
Daiichi Koide  Non-member (NHK Science and Technology Research Laboratories)
Yoshimichi Takano  Non-member (NHK Science and Technology Research Laboratories)
Haruki Tokumaru  Non-member (NHK Science and Technology Research Laboratories)

Keywords: optical disk, tracking control, offset, high order harmonics

Recently, Blu-ray Disc (BD) is being used as the next generation optical disk. The track pitch of BD is 320 [nm], and the disk rotation speed is high for realizing a fast data-transfer rate. The maximum disk rotation speed of BD is limited to 10,000 [rpm]. Moreover, the development processes of thin optical disks has advanced. The track pitch of a thin optical disk is less than 300 [nm], and a disk rotation speed of 15,000 [rpm] is possible.

A tracking control system for the next-generation optical disk drives is required to have high precision control at high disk speeds. However, it is difficult to employ a feedforward control system for the optical disk system because the reference signal of a tracking control system is unknown. For the purpose of suppressing residual tracking error, a ZPET control system using tracking error prediction has already been proposed. This control system suppresses the primary harmonic of residual tracking error. However, this control system does not suppress residual high-order harmonics and offset of tracking error.

This paper proposes a control system for suppressing tracking error offset and multiharmonic disturbance in high-speed optical disk systems. The proposed system suppresses residual tracking error, including primary harmonics, high-order harmonics disturbance, and offset. In addition, the cause of the offset of residual tracking error is discussed. The cause is found to be the operation error in the fixed-point DSP and the phase lag of the LPF. The proposed system is designed for CD and DVD experimental devices. The disk rotational speed in the experiments is 7,200 [rpm]. The experimental results for the DVD experimental device show that the residual tracking error is suppressed to 11.9 [nm_{pp}] and the tracking error offset is suppressed to 0.15 [nm]. The experimental results confirm that the proposed system enables an optical disk system to achieve a fine tracking performance.

Fig. 1. Proposed ZPET control system with control system for suppressing tracking error offset and multiharmonic disturbance

Fig. 2. Experimental results for conventional only ZPET control system

Fig. 3. Experimental results for proposed tracking control system
Robust Design of Vibration Suppression Control System for Crane Using Sway Angle Observer Considering Friction Disturbance

Hiroki Sano  Student Member  (Nagaoka University of Technology, seiyaku@stn.nagaokaut.ac.jp)
Kentaro Sato  Student Member  (Nagaoka University of Technology, s105016@stn.nagaokaut.ac.jp)
Kiyoshi Ohishi  Senior Member  (Nagaoka University of Technology, ohishi@vos.nagaokaut.ac.jp)
Toshimasa Miyazaki  Member  (Nagaoka University of Technology, miyazaki@vos.nagaokaut.ac.jp)

Keywords: crane control, state observer, disturbance observer, model error, vibration suppression, robust stability

It is desirable for a container crane to operate smoothly and quickly. The sway of a crane cargo container decreases the efficiency of the crane and bases a safety hazard. Moreover, the anti-sway control techniques for the container crane becomes the important specification on the viewpoint of the demand of efficiency and automation.

This paper proposes a new anti-sway crane control system based on a state observer of the sway angle. This paper discusses the use of the sway angle observer for estimating the sway angle of a container on the basis of the crane motion equation. However, when there is a variation in the parameters of the container crane, such as the rope length and load weight, the state observer does not estimate the sway angle accurately and there is an estimation error. In order to overcome this problem, this paper proposes another state observer that uses a vision sensor system to determine the sway angle. However, since a control system with a vision sensor has a delay time when determining the angle, it sometimes loads to the deterioration of the control performance owing to the delay time.

In order to overcome this problem, this paper proposes a new anti-sway crane control system based on a dual-state observer with sensor-delay correction. The poles of the observer are designed to have frequency characteristics that match the frequency characteristics of the control system when the measured sway angle is determined. The characteristics are shown in Fig. 1. However, because of nonlinear friction in the crane, the estimation accuracy achieved by using the observer is poor. To overcome this problem, this paper proposes a disturbance observer considering friction disturbance. The proposed system is shown in Fig. 2.

Fig. 3 shows experimental results for the case where the robust length of the rope shows variations upto $-10\%$. The proposed method suppresses vibrations by $86\%$, and it is therefore superior to the conventional method.

![Fig. 1. Frequency characteristics of the control system based on a state observer](image1)

![Fig. 2. Block diagram of the proposed control system](image2)

![Fig. 3. Experimental results (Robust length of the rope shows variations upto $-10\%$)](image3)
Motion Mode Decomposition
Based on Discrete Fourier Series Expansion

Yoshiyuki Hatta Student Member (Yokohama National University, hatta@tsl.dnj.ynu.ac.jp)
Tomoyuki Shimono Member (Yokohama National University, shimono@ynu.ac.jp)

Keywords: haptics, motion control, bilateral control, modal decomposition, discrete Fourier series expansion, motion recognition

Recently, several methods for decomposing the whole motion of a parallel multi-degrees-of-freedom (MDOF) system into motion modes have been proposed. A motion mode is a motion element that corresponds to a specific physical action, such as grasping, manipulating, and rotating. Modal decomposition is effective for the expression and analysis of a complicated motion. However, the conventional method based on the Hadamard matrix or Quarry matrix has an application limitation based on the number of degrees of freedom (DOF). Although the conventional method based on the discrete Fourier transformation (DFT) solves this problem, the calculation of complex numbers is required. Moreover, if the arrangement of actuators in the system does not have spatial linearity and symmetry, the conventional methods cannot easily extract the motion modes.

In this paper, a novel modal decomposition method based on the discrete Fourier series expansion (DFS) is proposed. A parallel MDOF system can be considered that it has “Spatial periodicity”, as shown in Fig. 1. Then, the spatial periodic function can be represented as the combination of a direct component and alternate components by DFS. Each Fourier coefficient expresses each motion modal information. The proposed modal decomposition method only requires the calculation of real numbers, and it does not have an application limitation based on the number of DOF. Thus, the proposed method can be applied, even if the arrangement of actuators does not have spatial linearity and symmetry.

This paper also proposes a bilateral motion control method based on DFS modal decomposition, as shown in Fig. 2. The bilateral control method can realize haptic communication even if the arrangement of a master system is different from that of a slave system, as shown in Fig. 3. The validity of the proposed method was verified on the basis of some experimental results. Fig. 4 and Fig. 5 show the results of the spatially asymmetric haptic system shown in Fig. 3. Fig. 4 shows modal information corresponding to position response, and Fig. 5 shows modal information corresponding to force response. Position tracking is realized, and the “law of action and reaction” is satisfied in the modal space. It can be said that precise haptic communication is achieved by the proposed bilateral control method based on DFS modal decomposition.
Object-Coordinate-Based Bilateral Control System Using Visual Information

Yu Nakajima, Student Member (Keio University, nakajima@sum.sd.keio.ac.jp)
Takahiro Nozaki, Student Member (Keio University, takahiro@sum.sd.keio.ac.jp)
Yuji Oyamada, Student Member (Keio University, charmie@hvrl.ics.keio.ac.jp)
Kouhei Ohnishi, Senior Member (Keio University, ohnishi@sd.keio.ac.jp)

Keywords: haptics, master-slave system, bilateral control, computer vision, visual servo, posture estimation

Recently, teleoperation techniques have been widely developed. A bilateral control is one of the solutions that enable humans to experience a tactile sensation for remote targets. However, it is difficult for operators to control this system because the information obtained by the operators is delayed and restricted. This is because the operators cannot see the remote target completely; otherwise, information is transmitted with delay and noises.

In order to solve this problem, the system itself must perform some tasks autonomously to help the operator. The system is required to obtain information about the remote targets, such as their posture or position. In this study, a camera is used to determine the posture and position of the targets. Moreover, an object coordinate, which is a coordinate based on the posture of the targets, is defined and a control system is constructed on the basis of the defined coordinate. Since, the object coordinate is based on the posture of the targets, the operators can experience a tactile sensation without manually tracking the position or posture of the targets.

Fig. 1 shows the experimental setup. The control goals are as follows:
- bilateral control along the vertical coordinate
- position control along the horizontal coordinate

The experiment involved free motion and contact motion of the target. The shaded area indicates contact motion in each figure.

Firstly, Fig. 2(a) and Fig. 2(b) show the position and force responses, respectively along the vertical coordinate. As for the position response, it is confirmed from Fig. 2(a) that the master robot position follows the slave robot position. In Fig. 2(b), the blue line indicates the reaction force of master robot. The red line indicates the reaction force of slave robot calculated online by using visual information. The green line indicates the reaction force of the slave calculated offline by using the actual angle measured by the encoder. Since, the sum of the forces denoted by the blue and green lines become 0 N, the action- and reaction-force law holds true in this case.

Lastly, the position response on horizontal coordinate is shown in Fig. 3. “Cmd” indicates the position of the target calculated by the camera, and “Res” indicates the response value. Fig. 3(b) indicates the error, and it had the maximum value of 1.5 mm, which implies that the robot tracked along the center of the target.
Deployment Control of Wireless Multi-Hop-Relay Mobile Robots Based on Voronoi Partition

Takaaki Imaizumi Student Member (Shibaura Institute of Technology)
Hiroyuki Murakami Member (YASKAWA Electric Corporation)
Yutaka Uchimura Member (Shibaura Institute of Technology)

Keywords: Voronoi partition, rescue robot, distributed control, wireless network, mobile robot

Recently, research and development of rescue robots used in disasters has attracted considerable interest. The rescue robots are expected to explore a devastated area and gather information on the front line of the disaster. When manipulating rescue robots, wireless LAN (WiFi)-based tele-operation is a promising technology compared to conventional radio control. In particular, a multi-hop adhoc network can extend the transmission distance of end-to-end stations by increasing the number of stations. To maintain transmission connectivity between the robots, one of the options is to use a packet relay with wireless stations that are equipped on mobile robots. The issue is where to deploy the relay robots. To address the issue, we apply a Voronoi-diagram-based approach that was recently studied for the coverage problem in the field of mobile sensor networks.

The VECtor-based Algorithm (VEC) is one of the Voronoi-partition-based algorithms. It is based on the principle of moving sensors from densely deployed areas to sparsely deployed areas. The mobile sensor coverage problem is similar to our problem in this study.

This paper proposes a control scheme that facilitates the optimum deployment of multi-relay-robots based on a modified VEC method that positions the mobile relay robots appropriately to maintain the multi-hop network. In the method, a virtual force that drives a node to the centroid of Voronoi neighbors maintains the connectivity of wireless communication.

In order to evaluate the proposed method in a real environment, we conducted an experiment by using the mobile robot shown in Fig. 1. An overview of the experimental field is shown in Fig. 2.

Fig. 3 shows the trajectories of two relay robots that were controlled by the proposed method. The experimental result shows that the two relay robots followed the motion of the leader robot and one of them turned at the corner. This result shows that the proposed method is valid for the autonomous distributed control of relay robots through a wireless multi-hop network in a real environment.
Contactless Magnetic Gear for Robot Control Application

Hiroki Komiyama Member (NIKON CORPORATION)
Yutaka Uchimura Member (Shibaura Institute of Technology)

Keywords contactless magnetic gear, cogging torque, two mass system, speed control, position control, force sensorless bilateral control

This paper describes the application of a magnetic gear to a robot by fulfilling the essential requirements for robot control, which are velocity control, position control, and force control. A magnetic gear is a transmission device that realizes contactless torque transmission by applying a magnetic force. When using a magnetic gear, cogging torque and spring characteristics need to be considered. Conventional studies mainly focused on analysis of the magnetic characteristics of a device. The disturbance effect due to cogging torque on motion control applications has not been well researched in these studies. In this paper, we introduce an approximate model of cogging torque. This model is used for velocity control to attenuate the disturbance due to cogging torque. In the case of position control, the oscillations due to the spring effect of the magnetic attractive force become a problem. To reduce the adverse effect due to these oscillations, resonance ratio control is applied. We also propose to use a magnetic gear for realizing the force-sensorless bilateral control of teleoperation. Thanks to the frictionless transmission of a magnetic gear, the force-sensorless estimation of a reaction force can be realized using a reaction force observer.

In this study, we studied two types of magnetic gears. The first device, shown in Fig. 1(a), is called magnetic coupling, which transfers drive torque a perpendicular direction. We used this coupling for velocity control and position control. The second device, shown in Fig. 1(b), consists of two pairs of magnetic reduction gear and can achieve a reduction speed ratio of 16:1.

Cogging torque, which deteriorates the performance of velocity control, depends on the angle of the motor and can be estimated from this angle; thus, we applied feed-forward control to attenuate the effect due to cogging torque. In the case of position control, a magnetic force functions as a spring factor, which induces an oscillated response, as shown in Fig. 2 by the black solid curve. To avoid this, we applied resonance ratio control with a disturbance observer. The solid gray curve in Fig. 3 shows the response when applying the proposed control.

Force-sensorless bilateral control is also proposed in this paper. Thanks to the superior back-drivability of a magnetic gear, the reaction force can be accurately estimated without a force sensor. By using a reaction force observer and 4-channel controller, force-sensorless bilateral control was realized. Fig. 4 shows a block diagram of the control setup.

Fig. 1. Two types of magnetic gears

Fig. 2. Approximate modeling of cogging torque

Fig. 3. Experimental results in the case of position control

Fig. 4. Block diagram of bilateral control
Development of Two-link Manipulator Equipped with Biarticular Muscle Mechanism Using Flexible Actuator

Yuki Saito  Student Member (Keio University, ysaito@sum.sd.keio.ac.jp)
Wataru Motooka Non-member (Keio University, motooka@sum.sd.keio.ac.jp)
Takahiro Nozaki Student Member (Keio University, takahiro@sum.sd.keio.ac.jp)
Daisuke Yashiro Member (Keio University, yasshi@sum.sd.keio.ac.jp)
Kouhei Ohnishi Senior Member (Keio University, ohnishi@sd.keio.ac.jp)

Keywords: biarticular muscle, flexible actuator, antagonistic drive, monoarticular muscle

Nowadays, many power-assisted and rehabilitation robots are being researched and developed. However, conventional robot technology is intended for use in the industrial field. Therefore, conventional robot technology is not safe enough. Thus, it is necessary to further develop robot technology for realizing innovative biological mechanisms. This paper focuses on a biarticular muscle mechanism.

In this study, a novel mechanism for two-link manipulators with two antagonistic monoarticular muscle mechanisms and one antagonistic biarticular muscle mechanism, shown in Fig. 1, is developed. The monoarticular and biarticular muscle mechanisms are actuated by flexible actuators that consist of linear motors and thrust wires. In addition, a biarticular control system is proposed for the developed two-link manipulators. The problem of torque sharing is solved by utilizing an inverse moment arm matrix represented by Eq. (1), Eq. (2), and Eq. (3).

\[ \tau = G' T \]  \hspace{1cm} (1)
\[ G' = \frac{1}{D} \begin{pmatrix} d_1^2 d_2^2 + d_1 d_2 d_3^2 & -d_1 d_2^2 \cr -d_1 d_2^2 & d_1^2 d_2^2 + d_2 d_3^2 \end{pmatrix} \]  \hspace{1cm} (2)
\[ D = d_1^2 d_2^2 + d_1 d_2 d_3^2 + d_2 d_3^2 \]  \hspace{1cm} (3)

Where, \( \tau \) is the matrix of the torque output of the antagonistic muscles, \( T \) is the matrix of the torque at the joints, \( G' \) is an inverse moment arm matrix, and \( d_1, d_2, \) and \( d_3 \) are desired real numbers.

The antagonistic muscle system and torque sharing are controlled by the proposed control system. Experiments were performed in which three patterns of inverse moment arm matrices were used. The position responses and force outputs of the biarticular muscle mechanisms are shown in Fig. 2. The experiments confirmed that the robot achieved high-accuracy positioning and control of the force output of biarticular muscle mechanisms by the inverse moment arm matrix.
Mechanism of Shaft End-To-End Voltage Generation by Asymmetry in an Inverter-Driven Motor

Yusuke Asakura  Student Member (Tokyo Institute of Technology)
Hirofumi Akagi  Senior Member (Tokyo Institute of Technology)

Keywords: shaft end-to-end voltage, asymmetry, EMI, motor drives

This paper deals with the shaft end-to-end voltage resulting from asymmetric stray capacitances in an inverter-driven motor. The term “shaft end-to-end voltage” is used as the voltage between the shaft drive and nondrive ends in the axial direction, and it is represented as $v_{\text{shaft}}$. The test motor is an industrial grade three-phase induction motor rated at 400-V, 15-kW, 4-pole, and 50-Hz, which has randomly-wound distributed double-layer stator windings.

Fig. 1 shows a crosssection of the motor. Silver brushes installed at the shaft drive and nondrive ends are in electric contact to observe the shaft end-to-end voltage. The origin of the voltage can be any of the following: a ground leakage current, dielectric breakdown in bearings, and asymmetric stray capacitances on stator windings. The third origin seems to be related to the differential-mode current, but the details of the relationship have not been clarified. In this study, differential-mode tests are carried out on the ungrounded motor, and the shaft end-to-end voltage generation by the asymmetric stray capacitances is theoretically discussed.

In the following experiments, two linear amplifiers are used for supplying a single-phase sinusoidal differential-mode current in a frequency range from 10 kHz to 2 MHz to the test motor when the motor is not running. This special arrangement makes it possible to measure only the shaft end-to-end voltage caused by the third origin. Generally, stator windings have asymmetric stray capacitances. The capacitances induce a current flow that is equivalent to a common-mode current $\Delta i_{\text{L}}$ flowing to the axial direction. Fig. 2 shows the relation between $\Delta i_{\text{L}}$ and $\Delta \phi_{\text{DM}}$ in a simplified cut model where $\Delta i_{\text{L}}$ produces magnetic flux $\Delta \phi_{\text{DM}}$ in the stator core. As a result of the magnetic flux production, a shaft end-to-end voltage is generated.

This paper presents a winding model of the motor for the purpose of understanding the generation mechanism of the shaft end-to-end voltage. The model expresses a single-phase winding as a distributed-constant circuit. By using the model, $\Delta i_{\text{L}}$ can be simulated. Fig. 3 shows a comparison between experimental and simulation results. The frequency dependency of $\Delta i_{\text{L}}$ agrees well with that of the shaft end-to-end voltage. This means that $\Delta i_{\text{L}}$ is the cause of the shaft end-to-end voltage.
Estimation of Optimal Measurement Position of Human Forearm EMG Signal by Discriminant Analysis Based on Wilks’ lambda

Atsushi Kiso Student Member (Chiba Institute of Technology)
Yu Taniguchi Non-member (Chiba Institute of Technology)
Hirokazu Seki Member (Chiba Institute of Technology)

Keywords: myoelectric signal, optimal measurement position, discriminant analysis, wilks’ lambda, human forearm motion discrimination

This paper describes the estimation of the optimal measurement position by discriminant analysis based on Wilks’ lambda for myoelectric hand control. Fig. 1 shows an example of a myoelectric potential waveform. Fig. 3 shows Wilks’ lambda according to the number of selected positions.

In previous studies, for motion discrimination, the myoelectric signals were measured at the same positions. However, the optimal measurement positions of the myoelectric signals for motion discrimination differ depending on remaining muscles of amputees. Therefore, the purpose of this study is to estimate the optimal and fewer measurement positions for precise motion discrimination of a human forearm. This study proposes a method for estimating the optimal measurement positions by discriminant analysis based on Wilks’ lambda, using the myoelectric signals measured at multiple positions. The process of the optimal measurement position estimation method is shown in Fig. 2. In this study, six types of motion, namely, “Open,” “Grasp,” “Flexion,” “Dorsiflexion,” “Pronation,” and “Supination,” are used as the identification target motions.

In this study, 20 pairs of RMS values of eight channels are prepared for each identification target motion, and each motion groups are distinguished. In addition, the motion groups are distinguished according to Mahalanobis’ generalized distance. Then, the optimal measurement positions are selected by the stepwise forward selection method. The discriminant precision at the selected positions is confirmed on the basis of the value of Wilks’ lambda. Wilks’ lambda value becomes 0–1. If the value is close to 0, the discriminant precision is high. This study estimates the optimal measurement positions for three healthy people (subject A, B and C). Fig. 3 shows the values of Wilks’ lambda according to the number of selected positions. With an increase in the number of the selected position, the value approaches 0. The change in the value becomes small after the number of the selected position becomes three. Therefore, the first three selected positions are the optimal measurement positions.

In this study, motion discrimination is realized using the fuzzy inference method. Motion discrimination is performed on the basis of the myoelectric potential measured at “the optimal position” and “the normal position”. As for the number of the myoelectric sensors, the optimal position is three and the normal position is four. In these experiments, the three subjects (A, B and C) are the same as those who participated in the optimal position estimation experiments. Fig. 4 shows the experiment results. High discrimination precision was verified for all subjects by measuring the myoelectric potential at each optimal position.
An Adjusted Current Control System for Signal-injection-based Position Sensorless Control and Parameter Identification

Suk-Hwa Jung  Student Member  (Nagoya University, jung@nagoya-u.jp)
Takumi Ohnuma  Member  (Numazu National College of Technology, ohnuma@numazu-ct.ac.jp)
Shinji Doki  Senior Member  (Nagoya University, doki@nagoya-u.jp)
Shigeru Okuma  Senior Member  (Nagoya University, okuma@nagoya-u.jp)
Masami Fujitsuna  Senior Member  (DENSO CORPORATION, masami_fujitsuna@denso.co.jp)

Keywords: current control, signal injection, signal separation, position sensorless control, parameter identification

This paper proposes a current controller for signal-injection-based control schemes such as those for parameter identification and position sensorless control. In a conventional current control system with voltage signal injection, the separation of the injected frequency components from the current is carried out by using bandstop filters (BSFs). However, the separation is not accurate, especially when the system is in the transient state and when the current controller bandwidth is close to the injected signal frequency. This leads to the distortion of the transient response and affects the stability of the current control system. Fig. 1 shows the frequency characteristics without filters, the theoretical characteristics, and experimental results obtained by considering the d and q axes when the BSFs are used. These results indicate that the BSFs’ center frequency characteristics and its low- and high-frequency characteristics are largely distorted.

The proposed controller estimates the injected frequency components in the current on the basis of a motor model by using the injected signal as the input. Therefore, accurate signal separation is accomplished even in the transient state. Moreover, the current controller’s stability and dynamic performance are improved significantly. The frequency response is given in Fig. 2. It can be said that the characteristics are improved to a large extent.

The proposed system estimates the high-frequency current components along with the parameters of the motor in the digital controller. There are some sources that contribute to the estimation error; filters used in the current measurement, zeroth order hold (ZOH) and parameter variation. The delays introduced by the filters and ZOH are analyzed. The variation in the inductance can be obtained by performing an off-line experiment, and it can be used to compensate for the magnetic saturation effect.
Rotor Position Sensorless Control and Its Parameter Sensitivity of Permanent Magnet Motor Based on Model Reference Adaptive System

Masaki Ohara Member (Shizuoka University, Takenaka Seisakusho Co., Ltd.)
Toshihiko Noguchi Member (Shizuoka University)

Keywords: model reference adaptive system, permanent magnet synchronous motor, rotor position sensorless control, parameters sensitivity

The development of a rotor position sensorless control technology for permanent magnet synchronous motors (PMSMs) has brought low-cost, noise-free and space-saving to controllers and PMSMs. Several methods for estimating the rotor speed and position have been particularly developed for the middle and high-speed regions. For example, the one method is to use a four-dimensional adaptive observer on a stator axis or rotor axis which predicts the flux of the PMSM, and the other is to use a disturbance observer that predicts the expanded induced voltage determined using the voltage current equation of the PMSM.

This paper describes a new method for a rotor position sensorless control of a surface permanent magnet synchronous motor based on a model reference adaptive system. Fig. 1 shows the configuration of our proposed method of the rotor position sensorless control system. The difference between this method and others is that the control system includes a model reference adaptive system in a current control loop to estimate the rotor speed and position using only current sensors.

However, this method as well as almost all the conventional methods includes a mathematic model of the motor that consists of parameters such as winding resistances, inductances, and an induced voltage constant. Hence, the important thing is to study how the fluctuation of parameters is associated with the desired position since such fluctuations affect the performance of the sensorless control.

This paper proves the stability of the method when the parameters of the motor deviate from parameters of the model, and derives the relational equation between the desired position and the fluctuation of parameters in a steady state. Fig. 2 indicates an example of the relation between the rotor position and the resistance in the steady state. The thick line is an ideal curve. We can see that the ideal value fits the actual value. Fig. 3 shows an example of the transient responses of the PMSM when a full load torque suddenly changes under –10% fluctuation of the induced voltage constant. These experimental results show the performance and verify the effectiveness of the proposed method.

Fig. 1. Configuration of rotor position sensorless control system

Fig. 2. Fluctuations of parameter (winding resistance)

Fig. 3. Step response for disturbance load during fluctuations of induced voltage constant
Proposal and Error Evaluation of Distance Sensor Based on Magnetic Resonance Coupling

Sousuke Nakamura Student Member (The University of Tokyo)  
Ryo Koma Non-member (The University of Tokyo)  
Takashi Kubota Non-member (The University of Tokyo)  
Hideki Hashimoto Senior Member (Chuo University)

Keywords: distance sensor, magnetic resonance coupling, novel configuration, distance error, Q factor

Distance and position sensors based on the electromagnetic field have potential applications in situations where occlusion of peripheral objects and illumination changes occur frequently. Distance and position are estimated from the measured electromagnetic energy exchange between the transmitter and the receiver. Currently, electromagnetic coupling and electromagnetic waves are used to estimate electromagnetic energy exchange. It is well known that the estimation accuracy is high for electromagnetic coupling while the electromagnetic energy is severely attenuated with distance. Therefore, the use of magnetic resonance coupling has been proposed as a supplement to amplify the electromagnetic energy.

In the case of conventional sensors based on magnetic resonance coupling, it is assumed that long distances can be estimated at a high Q factor. However, theoretical considerations have not been made because it is difficult to express the relation between the distance error and the distance analytically. In addition, not enough consideration has been given to the sensor configuration.

Therefore, a distance sensor based on magnetic resonance coupling with a novel configuration and error evaluation of the proposed sensor are discussed in this paper. In the error evaluation, the relation between the distance error and the distance is expressed semi-analytically by applying function approximation. The relation between the distance error and the distance is taken into consideration, particularly when changing the Q factor.

The proposed sensor has the configuration shown in Fig. 1. It is assumed that the transmitter antenna is fixed and that the target antenna can move over space. Batteries are required in the conventional configuration since the measuring device and the communication devices are connected to the target side. The proposed sensor has the advantage that the target side is completely free from batteries since the measuring device is connected to the transmitter side.

An algorithm using reflection coefficient as the measuring quantity is proposed for sensing. The reflection coefficient represents the degree of electromagnetic energy exchange between the transmitter and the target antenna, and it is dependent on the distance between the antennas. The algorithm runs in two phases. In the first step, the coupling coefficient is calculated analytically from the reflection coefficient. In the second step, the distance is derived by referring to the database of the relation between the coupling coefficient and the distance since this relation cannot be expressed analytically.

Error evaluation was performed by a semi-analytical approach. Since the relation between the coupling coefficient and the distance could not be expressed analytically, approximation using an exponential function was applied. As a result of the approximation, the distance error became proportional to the error rate of the coupling coefficient which could be expressed analytically. Therefore, the error rate of the coupling coefficient was analyzed instead of the distance error. Theoretical consideration of the effect of the Q factor on the relation between the error rate of the coupling coefficient and the distance was made. From the result, two conclusions were drawn. First, the error rate of the coupling coefficient was convex downward with respect to distance. Second, as the Q factor increased, the error rate increased and decreased when the distance was shorter and longer than the minimum distance (distance at which the error rate is the minimum), respectively. From the proportional relation between the error rate of the coupling coefficient and the distance error, it was concluded that the distance error is convex downward with respect to distance and the distance error increases and decreases when the distance is shorter and longer than minimum distance, respectively, as the Q factor is increased.

A verification experiment was performed for two Q factors using the experiment setup shown in Fig. 2. The experimental result was well consistent with the theoretical consideration. However, there was some error such as an unknown bias in the distance error. The experimental result for the relation between the actual distance and the estimated distance is shown in Fig. 3. Clearly, estimation of long distances is possible at a high Q factor. The obtained result can be used as a guideline for designing distance sensors.

In the future, a position sensor with an array of the proposed distance sensors will be realized and used in various applications such as localization of mobile robots.
Multiple-DC-Inputs Direct Electric Power Converter D-EPC with DC Power Sources Connected in Series

K antaro Yoshimoto Member (NISSAN MOTOR CO., LTD.)
Shou Satou Non-member (NISSAN MOTOR CO., LTD.)
Ken go Makawa Member (NISSAN MOTOR CO., LTD.)
Kouji Takahashi Non-member (NISSAN MOTOR CO., LTD.)

Keywords: power conversion, power control, bi-directional switch, inverter, fuel cell vehicle

A multiple-dc-inputs direct electric power converter (D-EPC) has been developed. Figure 1 shows the circuit diagram of the D-EPC. The D-EPC is placed between multiple dc power sources and an ac motor, thereby eliminating the need for a dc/dc converter that is generally used in conventional converter/inverter systems for fuel cell vehicles. D-EPC can help realize the power distribution control without the need for a dc/dc converter and is capable of charging the other power source while simultaneously powering the motor.

On the basis of the original D-EPC, a series-type D-EPC that can connect DC power sources as series has been developed. Figure 2 shows the circuit diagram of the series-type D-EPC. It has three input terminals, positive, negative and common terminals, since DC power sources are connected in series. The switch between the common terminal and the ac output terminal comprises bidirectional switches. In series-type D-EPC, the number of bidirectional switches is lesser than that in the original D-EPC shown in Fig. 1.

This circuit topology allows for series voltage output, and thus, the output ac power can be increased.

Power distribution control is realized by the output voltage distribution. D-EPC can be regarded as a system of two inverter circuits with one power source each. The circuit alternately activates one of the two inverter circuits in pulse width modulation (PWM) cycles. Then, the time-averaged voltage can be provided as voltage distribution command.

Figure 3 shows the experimental result of the power distribution control. The dc current from each power source is controlled as the power distribution command. Figure 4 shows the U-V line voltage in a short time-division. When the output voltage increases, the series voltage is outputted, as in Fig. 3.

In this paper, the power distribution control and PWM pulse generation method for a series-type D-EPC are described. These are experimentally verified by using a prototype circuit.