A Review of Saliency-based Sensorless Control Methods for Alternating Current Machines

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Keywords: sensorless speed and position control, AC machines, signal injection, machine saliencies, hybrid system, PWM based injection

1. Introduction

Model-based speed estimation in AC drives is possible at nearly all speeds; however, most model based methods fail at low or zero speed. The reason is that their speed estimation fundamentally depends on determining the back-electromotive force (emf) or the machine flux. At low speeds, the back-emf decreases to the extent that noise, inaccuracies in sampled variables, and inexact knowledge of the machine parameters yield relatively large estimation errors. In response, other methods that are independent of machine and inverter parameters aimed at estimating the rotor or flux position were developed.

Machine parameter — independent estimation at zero and low speeds is possible by tracking a form of saliency in a machine to derive the flux or rotor position. In the case of asynchronous machines, the saliency can be due to the rotating flux itself, the rotor slots or a specially engineered rotor. In the case of synchronous machines, the saliency is mainly caused by the magnetic saturation effect on surface permanent magnet synchronous motors and/or the geometric saliency of interior permanent magnet synchronous motors.

Additional signal injection for saliency detection can be categorized into two types; transient and continuous. Recently methods have been developed to detect saliencies excited either by selected switching states present in the inverter’s inherent Pulse Width Modulation (PWM) switching or by the PWM’s switching frequency itself. This paper reviews a number of sensorless methods applied to both asynchronous and synchronous motors. These methods were used to achieve zero/low speed control and/or position control of an AC machine drive system (Fig. 1).

Over the years various sensorless techniques have been developed to track saliencies for either flux tracking or rotor position tracking. The following are discussed in this paper:

1. HF Injection

The basic concept of HF injection is to excite HF currents that are dependent on a type of saliency. This can be applied to both asynchronous and synchronous machines. However, most types of machines are subject to multiple saliencies which can affect the HF-based method used. For correct position estimation these effects need to be mitigated. The paper considers alternative means of injection and introduces the concept of hybrid systems. The latter combines injection- and model-based estimation for a wider speed range operation.

2. Transient Injection

Transient injection differs from HF injection in that changes in the saliency-dependent machine impedances are detected by means of the current derivative response to repetitive transient excitation. The full paper presents ways of implementing such systems and discusses the idea of using injection together with an isotropic model for position estimation.

3. PWM-based Injection

PWM-based injection employs the inherent PWM switching as the excitation mechanism. These methods measure the resulting current transient response produced by standard (or slightly modified) PWM excitation. Although no additional signal injection or separate test vector is required, slight modification of the PWM by extended modulation or edge shifting could be required for short vectors. This paper shows how to implement this concept in practice and also discusses a relatively new method that employs the zero vectors present in PWM switching.

4. PWM Harmonic-based saliency detection

The harmonics related to natural switching in PWM voltages can be used to determine a HF saliency–dependent impedance from which the position can be estimated. Hence no additional test signal injection is required, and the fundamental control of the drive is unaffected. Operation at low/zero speed and excitation frequency is possible however, such methods require a complex predetermined machine–specific compensation table to decouple the additional modulation caused by saturation and inverter non-linearity.

Model-based, injection-based or a combination of these methods can be used to estimate the speed and position for sensorless control of AC machines. Research has shown that sensorless control of asynchronous and PM synchronous machines can cover all operating speeds and fundamental excitation frequencies through the use of hybrid systems or saliency detection techniques that were devised to work at low and higher speeds.

Fig. 1. Sensorless Control System
Owing to issues such oil depletion and global warming, the European market has been moving forward quickly with several energy saving and efficiency measures compared to other regions in the world. The measures will be required not only for individual components of a system such as electrical motors, but also for complete applications. These measures will be applied throughout the European region by means of the ErP (formerly EuP) directive and IEC standards. One of the most notable IEC standards defines the efficiency level required of induction motors classified by their power range, number of poles and input frequency. The efficiency levels were defined as three categories: IE1, IE2, and IE3. Recently, a fourth category was added (IE4) that applies not only to induction motors but also to all other types of electric motors. In Fig. 1 each efficiency level is shown for reference.

To meet these standards, each producer of AC motor drives in Europe has developed its own strategy with its own specific machine design and control techniques. Generally, variable torque applications such as fans, pumps and compressors account for approximately 70% of the European market. Such applications use drives with sensorless position and speed control. Owing to the price increase of rare earth magnets, many large drive companies started recommending magnet-less technologies with synchronous reluctance or IE4 induction motors. Owing to compactness and high-speed issues, however, the IPMSM has still been utilized in European market for specific applications, some of which are introduced in this paper. In this way, the use of sensorless AC motor drives has been steadily increasing throughout the European market, spreading to other applications such as concrete bearing cover inserter machines, and concrete cutting machines. In this paper, first the entire market trend of AC motor drives in Europe is described. Second, the market penetration of sensorless AC motor drives is briefly discussed. Finally, some real-life applications are introduced as shown in Figs. 3 and 4.
Fast Initial Position Estimation of IPMSMs Using Comb Filters

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Keywords: IPMSM, initial rotor position estimation, comb filter

This paper proposes a method for the fast initial position estimation of IPMSMs (interior permanent magnet synchronous motors) which is based on intentional pulse voltage injection and comb filters.

Generally, the rotor position can be estimated by detecting the high-frequency current caused by the injected high-frequency voltage because its response includes inductance information due to saliency. Some methods utilize the amplitude or differential value of the high-frequency current. These algorithms to calculate the saliency with its amplitude or differential value, however, appear to be complicated and unsuitable to improve the response of the position estimation. In particular, an algorithm for calculating the amplitude values requires some low-pass filters (LPFs) with a low cut-off frequency for the amplitude calculation, which degrades the response of the position estimation. Hence, a fast initial position estimation would be impossible. In order to overcome this problem, this paper proposes a new algorithm using comb filters which can rapidly calculate the amplitude values of the high-frequency current and improve the position estimation performance.

Figure 1 shows a block diagram of the proposed initial position estimation, in which the response of the position estimation depends on the DC component rejection and amplitude calculation algorithm. Figure 2 shows the block diagram of the proposed DC component rejection and amplitude calculation using comb filters. As can be seen in Fig. 2, the proposed algorithm enables fast initial position estimation because comb filters are simple and can be constructed without any LPFs which would degrade the sensorless control response. This paper has experimentally revealed the possibility of fast initial position estimation. Figure 3 shows the results of the initial salient-pole position estimation with the proposed algorithm. These results were obtained at the rotor position of −90° because the position estimation performance depends on the initial rotor position, and the rotor position of ±90° requires the longest time for the position estimation. A high-frequency pulse voltage was injected into the voltage reference in the γ-axis. The amplitude and the frequency of the injected high-frequency pulse voltage were 10 V and 1250 Hz. This figure demonstrates that the salient-pole position estimation was completed within 5 ms at most. In addition, Fig. 4 shows the results of magnetic polarity determination with the proposed algorithm. This paper utilizes the magnetic saturation in the d-axis for the polarity determination. Namely, ±1.5 A was sequentially superimposed as a DC component into the reference of the γ-axis currents, and then this paper determines the polarity by comparing the each integrated values of the amplitude of the high-frequency components in the γ-axis currents to improve its reliability. The magnetic polarity determination was completed within 4.8 ms, which is equal to 6 periods of the injected high-frequency pulse voltage. In conclusion, this paper realizes the initial position estimation within 9.8 ms at most as the total performance despite the use of the integrator for the position estimation as shown in Fig. 1.
Maximum Torque per Ampere and
Maximum Efficiency Control Methods based on V/f Control
for IPM Synchronous Motors

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Keywords: IPM synchronous motor, V/f control, maximum torque per ampere control, maximum efficiency control, reactive power

1. Introduction
Interior permanent magnetic synchronous motors (IPMSMs) have been extensively studied owing to their attractive features, high efficiency, high density, and high speed rotation. In order to eliminate the position sensor, several types of sensorless vector control methods have been studied and proposed for the IPMSM. However, the stabilization is difficult owing to inconsistent control parameters.

In this study, the characteristics of the maximum torque per ampere (MTPA) control strategy are clarified by experimental results. In addition, the maximum efficiency control method and the inductance identification method based on the V/f control are proposed.

2. High-efficiency Control Strategy based on V/f Control
Figure 1 shows the block diagram of the V/f control method based on the γδ-frame. The high-efficiency control block diagram shown in Fig. 1 was implemented to regulate the reactive power. In addition, the Qd∗ command value is calculated by (1) from the high-efficiency control block diagram.

\[
Q_{d\star} = \omega_r \left\{ L_d X^2 + L_q (I_a^2 - X^2) - \psi_m X \right\}
\]

where \(X = I_a \sin(\beta)\), \(I_a\) is the magnitude of the current vector, \(L_d(q)\) denotes the d(q)-axis synchronous inductance values, and \(\psi_m\) is the flux linkage of the permanent magnet. Here, the current phase \(\beta\) is given by (2).

\[
\beta = \sin^{-1} \left( \frac{\psi_m}{4(L_q - L_d) I_a} \right) + \sqrt{\left( \frac{\psi_m}{4(L_q - L_d) I_a} \right)^2 + \frac{1}{2}}
\]

Furthermore, the Qd∗ command value of the maximum efficiency control method based on the V/f control is calculated by (3) at the Qd∗ calc. block in Fig. 2.

\[
Q_{d\star} = Q_{dqref \_cmp} + \omega_r \left\{ L_d X^2 + L_q (I_a^2 - X^2) - \psi_m X \right\}
\]

Here, \(Q_{dqref \_cmp}\) is the reactive power reference compensation value, and this value is experimentally obtained.

3. Experimental Results
Figure 2 shows the experimental results of the IPMSM drive operation using the two-level inverter with the MTPA control method based on the V/f control method. The output current can be reduced by 68% after applying the MTPA control method.

Figure 3 shows the amplitude of the output current when the reactive power is varied by adding the error \(Q_{dqref \_vary}\) as (4).

\[
Q_d = Q_{dqref \_vary} + Q_{dqref \_cmp} + \omega_r \left\{ L_d X^2 + L_q (I_a^2 - X^2) - \psi_m X \right\}
\]
Model Predictive Direct Torque Control for PMSM with Discrete Voltage Vectors

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Keywords: permanent magnet synchronous motor (PMSM), direct torque control (DTC), model predictive control (MPC), optimization

1. Introduction
Several adjustable speed ac motors have been used in various fields with the recent advancements in the field of power electronics. In particular, permanent magnet synchronous motors (PMSMs) have received considerable attention owing to their advantages of low excitation loss, high power factor, high torque per current, and high efficiency. In fact, PMSMs have been widely adopted for commercial applications such as electric and hybrid vehicles.

This paper proposes a novel model predictive DTC (MPDTC) approach to reduce the torque ripple with a small number of switching operations while achieving a faster response at high speed. With this approach, the number of switching operations required for control is explicitly considered, which implies that the trade-off between the number of switching operations and the torque ripple can be addressed. In addition, the treatment of the dead-time in the inverter and the rotor rotation are also considered for practical use. The effectiveness of the proposed method is verified through simulations and experiments.

2. Preliminaries
As shown in Fig. 1, the state when the upper arm is conducted in each phase is denoted by 1, otherwise the state is 0. Both the arms are not conducted simultaneously for protection of the devices. The output voltage in each phase with the virtual neutral point is limited to $E_d$ or $-E_d$, for the dc-link voltage $E_d$. Then, the instantaneous output voltage of the inverter is confined to $2^3 = 8$ switching patterns.

3. Model Predictive Direct Torque Control (MPDTC)
The proposed MPDTC system is shown in Fig. 2. In the system, the MPDTC selects an optimal voltage vector from the finite voltage vector set $\{V_{000}, \ldots, V_{111}\}$ at each sampling. Frequent switchings lead to fast responses of the torque and the flux, but at the expense of losses in the devices in the inverter. The number of switching operations is also considered.

4. Simulations and Experiments
Figure 3 shows the experimental results of the torque response. From Fig. 3, it can be observed that the torque response of MPDTC is better than that by DTC.

5. Conclusion
In this paper, we proposed a model predictive direct torque control (MPDTC) for permanent magnet synchronous motors (PMSMs). In the proposed approach, the number of switching operations was taken into account as well as the torque and the flux responses. The effectiveness of the proposed method was verified through simulations and experiments. In both the simulations and experiments, MPDTC exhibited lesser torque and flux ripples in the steady state with a smaller number of switching operations, compared to DTC, at several operating points, achieving fast transient responses for the stepwise change in the reference values.
Experimental Study on a Restarting Procedure at Coasting Condition for a Rotational Angle Sensorless PMSM

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Keywords: permanent magnet synchronous motor, rotational sensorless control, starting procedure in rotating condition

One of the technical issues with the rotational angle sensorless controls for a permanent magnet synchronous motor (PMSM) is restarting problems when coasting. If the estimated rotor angle and speed have errors, the current is disturbed by back electromotive force (EMF). Therefore, the correct rotor angle and speed need to be quickly estimated when inverters start switching in the rotating condition.

According to the method in [1], the rotor speed can be estimated by the amplitude of the one-time three-phase short circuit current vector \(|I|\) considering the linearization waveform. This is shown by Eqs. (1) and (2)

\[
\begin{align*}
|I| &= \frac{L_q}{\Phi_f} \left( 1 - \cos \omega_{re} T \right) - \Phi_f L_d \left( 1 - \cos \omega_{re} T \right) \\
\omega_{re} &= \frac{L_q |I|}{\Phi_f T}
\end{align*}
\]

where, \(T\) determines the duration of the three-phase short circuit and is one of the most important design parameters for restarting under coasting conditions. However, the effect of the parameter has not been analyzed and there have been no papers on designing the parameter so far.

This study examined the restart conditions of the one-time short method when coasting by varying the duration of three-phase short circuit in experiments and numerical analysis. The effect of the linearized voltage equation on the error of the estimated rotor speed was quantified according to the experimental and numerical results (Fig. 1). The results showed that the duration of the three-phase short circuit should be changed according to the rotor speed upon detecting of the short circuit current to avoid the error due to linearization. The waveform of the current during the three-phase short circuit does not change at each speed. Thus, we propose an enhanced one-time short method with variable three-phase short circuit duration that sets a threshold value to the time response of the three-phase short circuit current (Fig. 2). The proposed method was verified experimentally (Fig. 3).

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Fig. 1. Numerical analysis results of short circuit currents

Fig. 2. Flowchart of proposed method

Fig. 3. Experimental results at 800 [rad/s]

References

Simplified Speed-Sensorless Vector Control for Induction Motors and Stability Analysis

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Keywords: speed-sensorless vector control, induction motor, root loci, linear model, stability analysis

For speed-sensorless vector control of induction motors, model-reference-adaptive-system-based methods have been studied in many works. However, the configurations of these systems are relatively complicated.

In this paper, we propose a new simplified method for speed-sensorless vector control of an induction motor, as shown in Fig. 1. When the rotor speed is unknown, the voltage model flux can be used to estimate the flux direction. The flux angle is adjusted by changing such that the flux of the voltage model becomes zero. This is obtained by the output of the d-axis PI current controller with a decoupling control, is proportional to the voltage model flux. We estimate as follows:

\[ \omega^* = \omega_i^* + \frac{i_{sq}}{r_i L_{sd}} - K_e e_{sq} \]

(1)

where \( K_e = \text{sign}(\omega^*) \left| K_{q} \right| \), \( \text{sign}(\omega^*) \) is 1 when \( \omega^* > 0 \) and -1 when \( \omega^* < 0 \). To control the speed, we compute as

\[ e_{sq} = \omega_i^* + \frac{i_{sq}}{r_i L_{sd}} + \frac{K_e}{S} e_{sq} \]

(2)

\[ T_{L} = A \Delta x + B \Delta \omega_i^* + B_\Delta \Delta T \]

(3)

System stability is discussed by using root loci by computing the eigenvalues of matrix \( A \). Figure 2 shows the unstable region when \( K_e = 5.0 \) and \( T_L = 0.05 \) for the changes of speed command and slip speed. The shaded areas are the unstable regions. Although an unstable region is observed in the plugging region and very low speed motoring region, all regenerating regions are stable.

The proposed control system is implemented by a DSP-based PWM inverter. The sampling period used in this system is 200 \( \mu \)s. The tested induction machine is 1.5 kV. Figure 3(a) shows the experimental results for the step change of the speed command for regenerating operations. The speed command is stepped from 50 min\(^{-1}\) to 150 min\(^{-1}\) and then down to 50 min\(^{-1}\). The simulation results computed by a non-linear model are shown in Fig. 3(b). A quick response in the speed \( \omega_i^* \) is obtained, and the changes in the torque current \( i_{sq} \) are similar to those of a vector control system with a speed sensor. The speed commands are similarly stepped as 500 → 600 → 500 min\(^{-1}\) and 1000 → 1100 → 1000 min\(^{-1}\). In any case, the experimental results agree well with the computed results except for high-frequency ripples. The high-frequency ripples of \( e_{sq} \) are caused by PWM voltage control. As a result, the effectiveness of the proposed method is demonstrated.
An Estimation Method for the Relation between a Robot System and Tasks Using Tool

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Keywords: motion control, task realization, visual sensor, parameter estimation

This paper proposes an estimation method for the relation between a robot system and the tasks using a tool. In order to perform intelligent tasks using a tool, it is necessary to estimate the relation between the robot system and tasks. However, there is no estimation method for this relation. Therefore, an estimation method that employs an external sensor is proposed. A visual sensor is utilized as one of the external sensors. In this study, this relation is treated as a task Jacobian matrix. From this viewpoint, an estimation method for the task Jacobian matrix that uses visual information is proposed.

Figure 1 shows the flowchart of the proposed method. Levenberg-Marquardt (LM) method is implemented for parameter estimation. In this method, the evaluation function $F$ is defined as follows:

$$ F = \frac{1}{2} \sum_{i=1}^{N} \sum_{p=1}^{2} F_p(q)^2 $$

where $F_1$ and $F_2$ are visual information for the tool translation and the tool rotation. $N$, $q$, and $x$ denote the number of the sampling data, the task Jacobian matrix related to the position, and the motor position vector measured by the encoders. As shown in Fig. 1, the update of visual information is checked first. Then, LM method is performed according to the value of evaluation function. By using LM method, the task Jacobian matrix $q$ to minimize the evaluation function is obtained.

Figures 2(a) and 2(b) show the experimental setup and the system configuration. Figures 2(c) and 2(d) show the experimental results without/with the proposed method. In Fig. 2(c), there are discrepancies between visual information and the position task responses. On the other hand, visual information is almost the same as the position task responses, as shown in Fig. 2(d). Therefore, the desired robot task using the tool is performed by using the proposed method. Figures 2(e) and 2(f) show the number of regression calculations and the value of the evaluation function. In Fig. 2(f), the value of the evaluation function is improved. From these results, the validity of the proposed method is confirmed.
Extended Summary

Data-Based Motion Control for Motion Reproduction for Automatic Adjustment of Environmental Location

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Keywords: bilateral control, disturbance observer, real-world haptics, motion-copying system, motion database

Recently, technology to save and reproduce haptic information (i.e., “haptic recording”) in a similar manner as for audio and visual information has come into demand. The motion-copying system (MCS) is one technology that can realize haptic recording. However, the MCS has difficulty in reproducing the position and force information if the environmental locations differ for loading and saving. The paper proposes a method to reproduce the saved motion according to the environmental location.

Figure 1 shows a block diagram of the proposed method. The superscripts \( \text{ref}, \text{res}, \text{ext} \) represent the reference, response value and external force respectively. The subscript \( \text{m}, \text{s}, \text{c}, \text{d} \) mean master system, slave system, common mode, and differential mode respectively. \( \hat{S}, \hat{C}, \hat{D}, \hat{Q} \) are the estimated value, position regulator, force servoing and second-order quarry matrix. First, the compensation values for the force and position are calculated as

\[
F_{\text{cmp}} = \frac{F_{\text{DATA}}}{S} - F_{\text{ext}} \tag{1}
\]

\[
x_{\text{cmp}} = \frac{x_{\text{DATA}}}{S} - x_{\text{ext}} \tag{2}
\]

where the superscripts \( \text{cmp} \) and \( \text{DATA} \) represent the compensation and the saved values respectively. Low-pass filters (LPF) are inserted, and the compensation values are added to the actual responses:

\[
F_{\text{ext}} = F_{\text{ext}} + \frac{\theta_{\text{pl}_f}}{S + \theta_{\text{pl}_f}} F_{\text{cmp}} \tag{3}
\]

\[
x_{\text{ext}} = x_{\text{ext}} + \frac{\theta_{\text{pl}_f}}{S + \theta_{\text{pl}_f}} x_{\text{cmp}} \tag{4}
\]

\( \theta_{\text{pl}_f} \) and \( \theta_{\text{pl}_l} \) are the cut-off frequencies of the LPF with force and position compensation respectively. \( \hat{S} \) represents the calculated value. (3) and (4) are rewritten as (5) and (6).

\[
F_{\text{ext}} = \frac{S}{S + \theta_{\text{pl}_f}} F_{\text{ext}} + \frac{\theta_{\text{pl}_f}}{S + \theta_{\text{pl}_f}} F_{\text{DATA}} \tag{5}
\]

\[
x_{\text{ext}} = \frac{S}{S + \theta_{\text{pl}_f}} x_{\text{ext}} + \frac{\theta_{\text{pl}_f}}{S + \theta_{\text{pl}_f}} x_{\text{DATA}} \tag{6}
\]

(5) and (6) mean that the force and position response are divided in the frequency domain. By varying the cut-off frequency of the LPF, the reproducibility of the force and position can be varied. When the environmental location differs, increasing the reproducibility of the force relative to that of the position allows the saved force information to be reproduced well.

In order to confirm the validity of the proposed method, experiments were carried out. First, a 10 s motion that included free and contact motions was saved. Second, the saved motion was reproduced in a different environmental location. Figure 2 shows the experimental results. Figure 2(A) shows that the position and force information were not both reproduced by the conventional method. Figure 2(B) shows the experimental results of the proposed method when \( \theta_{\text{pl}_f} \) and \( \theta_{\text{pl}_l} \) were 5000 and 10 rad/s. These results show that the force information was reproduced with more precision. Figure 2(C) shows that the position information was reproduced better when \( \theta_{\text{pl}_f} \) and \( \theta_{\text{pl}_l} \) were 10 and 5000 rad/s. By varying \( \theta_{\text{pl}_f} \) and \( \theta_{\text{pl}_l} \), the reproducibility can be varied. When \( \theta_{\text{pl}_f} \) is lower, the reproducibility of force is higher. In contrast, when \( \theta_{\text{pl}_l} \) is lower, that of position is higher.

The paper proposes a method for reproducing human motions when the environmental location differs. By varying the cut-off frequency of the LPF, the reproducibility of the force and position can be varied. When the environmental location is different, increasing the reproducibility of the force relative to that of the position allows the saved force information to be reproduced well. The effectiveness of the proposed method was verified experimentally.

Fig. 1. Block diagram of proposed method

Fig. 2. Experimental results for motion-loading system with differing environmental locations
An Evaluation of Connectivity and a Control in a Multilateral Communication System

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Keywords: multilateral control system, adjacency matrix, maximum eigenvalue, system connection, communication delay

The implementation of a technique that can share haptic information is expected for a brand new media if it is to replace the current multimedia technology that uses audio and visual information. A control system called a multilateral control enables the sharing of haptic information between several subsystems, making possible high transparency communication with remote places. However, the information tends to deteriorate under time delay. Communicating with several distant places inevitably involves various time delays inside the control loop, thereby destabilizing the control system and degrading the haptic information. Therefore, this paper proposes the method of selecting the best communication path in a multilateral control system for preventing information degradation.

To begin with, an index that enables the amount of information in each subsystem to be quantified is introduced. The index is called the “information volume” in this paper. The information volume is also a measure of the strength of each communication link. The information volume is calculated using the adjacency matrix $A^{CD}$. Conventional elements of the adjacency matrix are expressed as 1 or 0. In order to take time delay into account, each element contains information on the time delay in the corresponding communication links.

The information volume is a normalized value of the eigenvectors corresponding to the maximum eigenvalue of the adjacency matrix. The example of the information volume in Fig. 1(a) is shown as follows:

$$IV = [0.380, 0.353, 0.267]^T$$

where $IV$ is the information volume and the ith row shows the information volume in subsystem i.

Based on the value, the desired relationship of the information volumes that the master systems and the slave systems has is decided. One of the important points in multilateral control is to translate the information from the slave systems to the master systems. Therefore, assuming that there is one slave system in this study, connection links are to be selected to achieve the following inequality:

$$IV_S > IV_M \quad (i = 1, 2, \ldots, n-1)$$

where $IV_S$ means the information volume of the slave system, and $IV_M$ means the information volume of the master system i. The flowchart for selecting the best communication path that satisfies equation (2) is shown in Fig. 2.

Experiments were conducted to verify the validity of the proposed method. The conventional system connection is shown in Fig. 1(a), and the proposed system connection is shown in Fig. 1(b). Compared with the step response shown in Fig. 3, the proposed method oscillates less and the convergence of both the force and the position response is faster than it is in the conventional method.

This paper proposes an index that quantifies the amount of information each communication link contains. The paper then proposed the method to select the best communication path based on the information volume. The experimental results showed that the optimal path prevents degradation of the haptic information.
Prototyping for Robot Motion Design through Subjective and Objective Analyses

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Keywords: impression analysis, robot motion, 3D scenography, personal space, near-infrared spectroscopy.

This paper proposes a procedure to design robot motions by utilizing subjective and objective analyses for evaluating the impression of these motions. The procedure involving these methods consists of the following phases. Figure 1 illustrates the proposed prototyping procedure.

Phase 1
3D CG design for robot appearance and motion

Phase 2
Subjective analysis to investigate impression of robot motion

Phase 3
Objective evaluation of subjective impression results by brain monitoring

In Phase 1, several types of robot motion are prepared by considering the psychology of Anna Freud (1), the Kestenberg movement profile (2), and personal space (3). In Phase 2, the semantic differential (SD) method which is an orthodox analysis of impression is used. The SD method is effective at extracting statistical information from subjective answers, but the participants’ first impression may conversely weaken if there are many questions. Therefore, a modified two-step SD method is used to avoid this issue. In Phase 3, the impression difference for each robot motion is evaluated objectively using data measured by the brain monitoring system. The brain blood flow of participants who watched the robot motion was investigated by utilizing the near-infrared spectroscopy (NIRS) system. Results from the statistical t-test of the brain activity data measured at brain areas M1, BA 44, and Fp1 showed statistical differences for the changes in cerebral blood flow at Fp1 according to good impression and bad impressions as classified by the subjective analysis (p < 0.01), as shown in Fig. 2. These results showed appropriateness of the presented prototyping approach for robot motion design and impression evaluation.

Fig. 1. Prototyping procedure for robot motion

Fig. 2. Comparison of SBC mean value between CG robot motions with good and bad impressions (t-test, ** p < 0.01)

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Extended Summary

Particle Filter Vehicle Tracking Based on SURF Feature Matching

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Visual surveillance in dynamic scenes has become a very important research area of image processing and computer vision techniques in recent years, which attempts to detect, recognize, and track certain objects from image sequences, and more generally to understand and describe object behaviors. The utilization of image-based traffic surveillance includes analysis of the traffic flow and the status of road congestion, detection and avoidance of vehicle accidents, detection of vehicles with unusual behavior, and gathering of statistical information about roadway traffic. Vehicle tracking plays an important role in traffic surveillance because it provides dynamic information about the position of a tracked vehicle in time.

This paper proposes a robust vehicle tracking method based on speed-up robust features (SURF) feature matching in a particle filter framework. In this framework, the color feature and the local binary pattern (LBP) texture feature are also combined to improve the representation of the tracking target. In this study, the local feature points of the tracking target were extracted with the SURF algorithm. Two evaluation criteria, P-value (see Table 1) and distance, are adopted to compare the results. Our approach demonstrates very promising performance. The experimental results clearly demonstrate the effectiveness of our proposed method.

In the matching stage, we adopt the nearest neighbor distance ratio (NNDR) to match feature points. In the tracking stage, owing to the deformation of the moving target, we propose the adaptive on-line update mechanism. It includes two stages, discarding bad feature points and adopting new feature points. The former mechanism is defined as

\[ P_{i,t} = (1 - \theta) \cdot P_{i,t} + \theta \cdot \delta_i \]  \hspace{1cm} \text{(1)}

where \( P_{i,t} \) is the probability of the \( i \)th feature point being in the target template at time \( t + 1 \) and \( \theta \in [0, 1] \) indicates the degree of the object change. The larger \( \theta \) is, the faster the object will change, and \( \delta_i \in [0, 1] \) is a factor of matching determination procedure. The latter mechanism is defined as

\[ U_{P_{i,t+1}} = \begin{cases} U_{P_{i,t+1}}, & \text{if matching is true} \\ 1, & \text{otherwise} \end{cases} \]  \hspace{1cm} \text{(2)}

where \( U_{P_{i,t}} \) represents the weight of the point in the matching set \( U_{M_t} \) that matches the \( i \)th point in the un-matching set \( U_{U_t} \). If the feature probability \( U_{P_{i,t+1}} \) exceeds a threshold, we will adopt this point as a new feature one. And experiments show that this mechanism has a strong adaptability for tracking condition changes. Furthermore, we also present an improved distance kernel function to update the weights of particles and achieve adaptive tracking. The flow of the tracking algorithm is described in the paper.

In the evaluation phase, we implement some state-of-the-art trackers including the SIFT-PF tracker, the mean shift tracker, and the single color feature tracker using three challenge sequences. Two evaluation criteria, P-value (see Table 1) and distance, are adopted to compare the results. Our approach demonstrates very promising performance. The experimental results clearly demonstrate the effectiveness of our proposed method.

Table 1. P-value evaluation of the tracking data set

<table>
<thead>
<tr>
<th>Target</th>
<th>Mean shift</th>
<th>Color-PF</th>
<th>SIFT-PF</th>
<th>Proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>0.378</td>
<td>0.433</td>
<td>0.556</td>
<td>0.352</td>
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<tr>
<td>V2</td>
<td>0.404</td>
<td>0.426</td>
<td>0.351</td>
<td>0.193</td>
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<tr>
<td>V3</td>
<td>0.565</td>
<td>0.280</td>
<td>0.503</td>
<td>0.194</td>
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</tbody>
</table>