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研究課題名（和文）Research development of the super leading safe and smart next generation robot based on breakthrough superior wideband force perception and outstanding robot artificial intelligence

研究課題名（英文）Research development of the super leading safe and smart next generation robot based on breakthrough superior wideband force perception and outstanding robot artificial intelligence

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研究成果の概要（和文）：人間とロボットの協働に対する必要性が高まるにつれて、人間とロボットの協調作業の応用は広範に進化してきた。相互作用の性能向上と安全性を保証するために、これらのロボットの開発は感覚システムの構築に重点を置いており、特に、ロボットが現実世界を探索し、人間の能力に近い方法で作業を行うことを可能にする触覚に重点を置いている。しかし、触覚は、ノイズ、摩擦、望ましくない周期性、帯域幅の制限といった課題に直面する。これらの問題は、ロボットの実行を危険にさらし、人命を危険な状況にさらす可能性がある。本研究では、これらの問題を解決するために、超広帯域・インテリジェントな力覚を実現し、安全な相互作用力制御を目指す。

研究成果の学術的意義や社会的意義
本研究は、人間の触覚(400Hz)よりもはるかに広い1kHzの超広帯域力覚を実現し、ロボットの力制御分野における記録となる。超広帯域・インテリジェントな力覚は、力制御性能を向上させるとともに、安全な相互作用を保証することができる。本研究で開発された技術は、人間とロボットの安全な相互作用の応用、スマート力覚、スマート力制御システムに有用であり、少子高齢化が進む日本の日常生活や産業において、人間と協働するロボットの発展に貢献する。

研究成果の概要（英文）：The ascending need of human-robot collaboration has led to the extensive evolution of human-robot interaction applications. To enhance the performance and guarantee the safety of interaction, the development of these robots has been focusing on building sensory systems, especially the tactile sensation that allows robots to explore the real world and carry out work in a manner close to human ability. However, tactile sensation encounters challenges of noise, friction, undesired periodicities, and bandwidth limitation. These problems can endanger the executions of robots and expose human lives to hazardous circumstances. This study aims at solving these problems by realizing the breakthrough super-wideband and intelligent force perception for safe interaction force control.

研究分野：Motion control

キーワード：Motion control　Force control　Intelligent sensing　Deep learning

１．研究開始当初の背景

Modern societies have been witnessing the flourish of robotic technology and its various applications in almost aspects of human life. Robots have been developed to assist patients in hospitals, serve customers in stores, collaborate with workers in factories, support for household work, interact with school students for teaching purpose, take part in surgery, entertain human with specific skills, and cooperate in rescuing people in hazardous situations. Eventually, the target of these robotic applications is to continuously improve the standard of human life at present and in the future. In these robotic systems, to establish the effective human-robot collaborations, not only the successfully collaborative executions are required but the safe interaction is also critical to be realized since these robots frequently perform tasks involving interaction with human or environments. To enhance the performance and guarantee the safety of interaction, the development of these robots has been focusing on building a sensory system whose operational function is as similar to human sensory mechanism as possible, especially the tactile sensation that allows robots to explore the real world and carry out work in a manner close to human ability.

However, force-sensor-based and force-sensor-less approaches to tactile sensation encounters challenges of noise, friction, undesired periodicities and bandwidth limitation. These challenges lead to the decline of the fidelity of force sensing, and can endanger the executions of robots and expose human lives to hazardous circumstances. Moreover, noise is inevitable in most control systems and noise characteristics are generally not time invariant, especially during long-time operation, or when the working environments change. The variable noise is usually unpredictable and makes it difficult to identify the noise characteristics in advance for noise suppression. Force information corrupted by variable noise will impair the reliability and safety of the robot control system. So far, most force sensing approaches have not considered the influence of variable noise on tactile sensation.

２．研究の目的

This study aims at solving the above-mentioned problems by realizing the breakthrough super-wideband and intelligent force perception for safe interaction force control. The superior wideband of 1 kHz and periodicity-cancellation force observer, and the deep-learning-based adaptive-noise-cancellation force sensing are the targets to be developed in this study for realizing the purpose of “How to realize the superior fine force perception for safe interaction force control”. The technology developed in this study is expected to be useful in safe human-robot interaction applications, smart force sensing and smart force control systems where high flexibility and adaptation to various working environments are important.

３．研究の方法

To achieve the purpose of realizing the superior fine force perception for safe interaction force control, the tactile sensation challenges of friction, undesired periodicities, bandwidth limitation, and variable noise must be overcome.

This study developed the superior wideband and periodicity-cancellation force observer to solve the problems of friction, noise, undesired periodicities, and bandwidth limitation. The superior wideband force perception of 1 kHz has been realized and successfully applied to attain a high-performance force control system. The bandwidth of 1 kHz is much wider than human tactile sensation (400 Hz), and is a record in the field of robot force control. Moreover, this study proposed the deep-learning-based adaptive-noise-cancellation force sensing to solve the problem of the variable noise. This method realizes variable noise attenuation to enhance the force sensing and force control performances in a force control system where noise characteristics are variant.

3.1 Superior wideband and periodicity-cancellation force observer

This study proposed a new sensor-less force observation approach configured by the periodicity estimation integrated singular spectrum analysis based disturbance observer (PEISSA based DOB) to solve the problems of friction, noise, undesired periodicities, bandwidth limitation, and to realize the superior wideband and periodicity-free force observer. The disturbance observer (DOB) is employed for realizing the robustness of the control system by estimating and compensating for the disturbance force. In the proposed method, the singular spectrum analysis (SSA) is designed to construct the SSA based DOB to significantly separate the essential components of force estimation by the DOB from extreme noise contamination, especially when the pole of the DOB is remarkably increased to 6280 rad/s (≈1 kHz). That makes the bandwidth of the force sensing considerably widened.

Moreover, to reduce the influence of static friction on the control system, dither signal is intentionally added into the control current to generate vibrations in the control system so that the effect of the static friction is lessened. In order to eliminate the undesired dither periodicity from the force sensation, the periodicity estimation (PE) is constructed based on the least squares method. The periodicity is identified by the estimations of its phase and amplitude. The superimposed periodicity is removed from the force sensation based on the estimated periodicity. The PE uses the estimated force given by SSA based DOB for its estimating process. Fig. 1 shows the block diagram of the proposed force control using PEISSA based DOB. Figs. 2, 3 and 4 show the structure of the DOB, the SSA algorithm, and the PE algorithm, respectively.

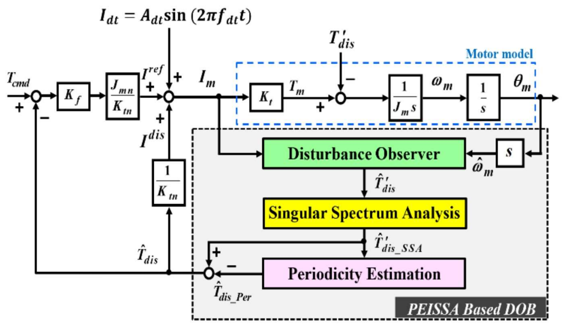

Fig. 1. Proposed force control using PEISSA based DOB

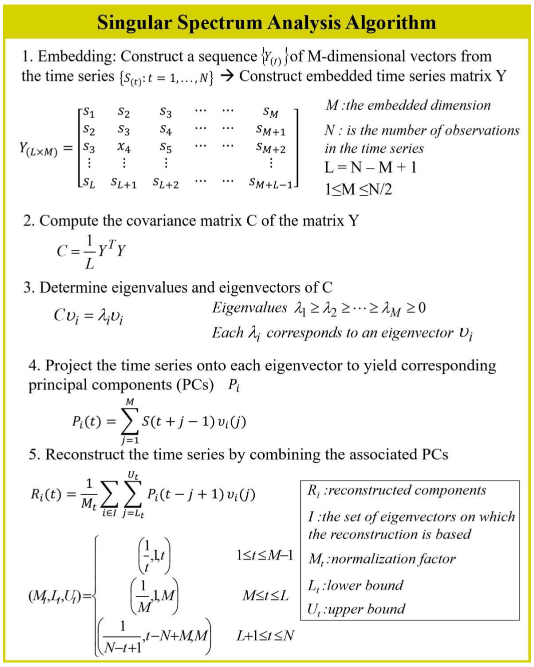

Fig. 3. SSA algorithm

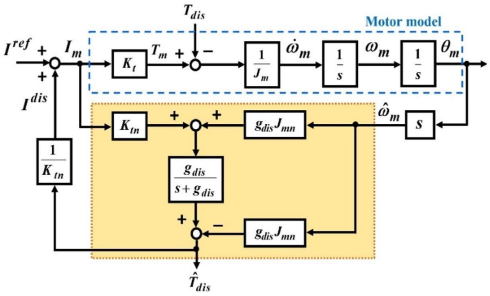

Fig. 2. Structure of the disturbance observer

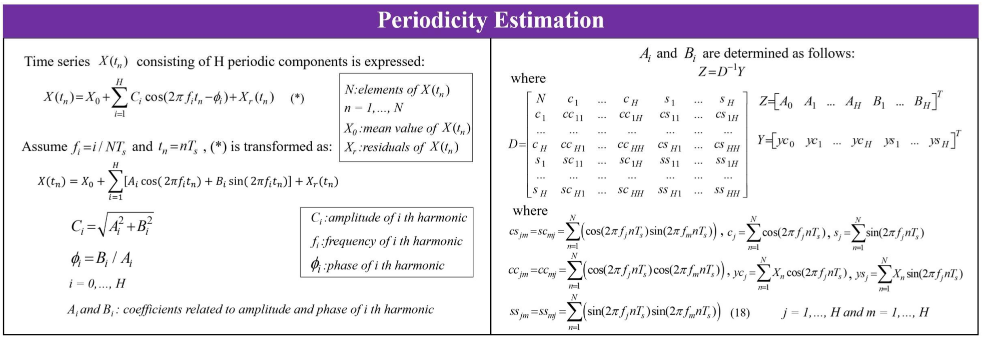

Fig. 4. PE algorithm

3.2 Deep-learning-based adaptive-noise-cancellation force sensing

This study proposed a new approach for adaptive-noise-cancellation force sensation to enhance the force sensing performance in a sensor-less force control system where the noise characteristics are variant. The proposed force sensing is constructed by the integration of the DOB and the deep learning (DL) based self-adjusting signal decomposition. The DOB is employed for the force estimation and disturbance compensation instead of using a force sensor. However, the force sensing performance of the DOB is degraded by noise, especially when the noise characteristics fluctuate. Hence, in the proposed method, the SSA associated with the DL based embedded dimension estimation is designed for the self-adjusting signal decomposition to cancel the effect of variable noise in the estimated force of the DOB.

The conventional SSA with a predefined number of eigenvalues is deficient in extracting noisy components in variable noise condition. For that reason, a deep neural network (DNN) modeled by deep learning algorithm is

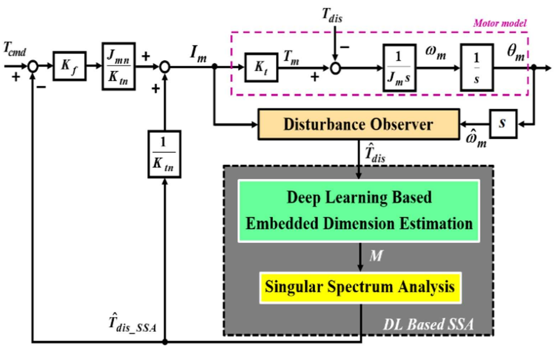

Fig. 5. Proposed force sensing using DL based SSA and DOB

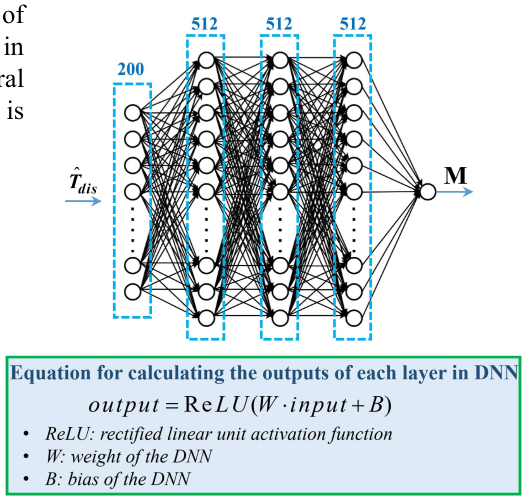

Fig. 6. Architecture of the DNN for embedded dimension estimation

created for self-determination of the number of eigenvalues, which decide the embedded dimension governing the performance of signal decomposition and noise extraction of the SSA. The self-adjusting signal decomposition of force information is realized when the number of eigenvalues is decided in real time. Accordingly, the adaptive noise cancellation for force sensation is also achieved. Hence, the proposed method attains the enhanced force sensing and force control performances under the influence of variable noise characteristics. Fig. 5 shows the block diagram of the proposed force sensing using DL based SSA and DOB. Fig. 6 presents the architecture of the DNN for embedded dimension estimation, and the equation for calculating the outputs of each layer in the DNN.

４．研究成果

4.1 *Superior wideband and periodicity-cancellation force observer to realize high-performance force sensing and force control*

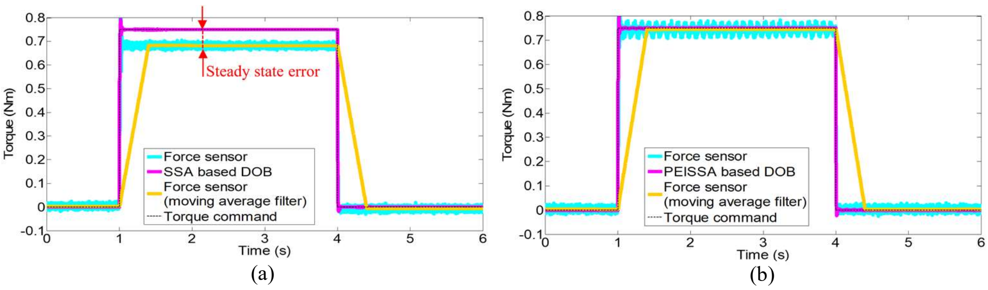

Fig. 7. Force control at DOB pole 6280 rad/s. (a) Using SSA based DOB without dither. (b) Using PEISSA based DOB with dither

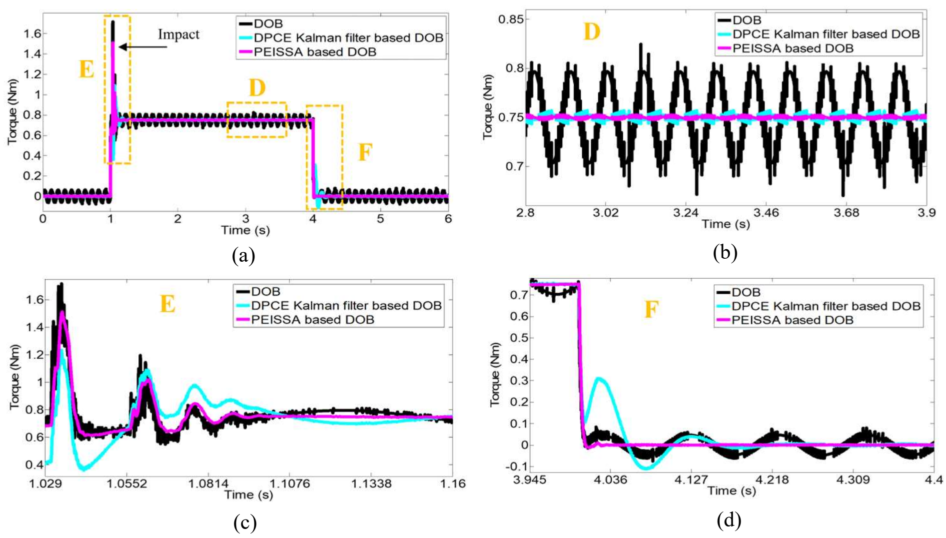

Fig. 8. Estimated torques of PEISSA based DOB and DPCE Kalman filter based DOB (conventional method) at DOB pole 6280 rad/s (with dither). (a) Torque estimations. (b) Magnified portion of contact condition (D range). (c) Magnified portion of impulsive response (E range). (d) Magnified portion of transient state (F range)

Because the purpose of this study is to achieve the superior wideband force sensing, the effectiveness of the proposed method is verified in the condition of DOB pole considerably raised to 6280 rad/s (≈1 kHz) in all experiments.

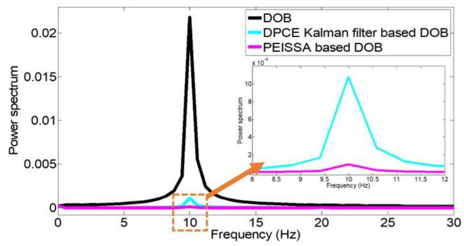

Fig. 9. FFT analysis of estimated torque presented in Fig. 8

The experimental results in Fig. 7 demonstrates the effect of dither signal on reducing static friction in the force control system. The results illustrate that a steady state error exists in the reaction force in the case of using SSA based DOB (without dither signal) due to static friction. However, the reaction force in the case of using the PEISSA based DOB (with dither signal) has significantly decreased steady state error owing to the reduction of static friction. Fig. 8 compares the performance of the proposed method with the conventional method (DPCE Kalman filter based DOB) to clarify the effectiveness of the proposed method. The results show that both methods suppress noise effectively under condition of extreme noise contamination at DOB pole of 6280 rad/s. The periodicity is significantly eliminated by both methods. However, the impulsive force estimation of the conventional method does not properly track the impulsive force response as shown in Fig. 8 (c). Moreover, the periodic component is not efficiently eliminated by the conventional method during the transient state as shown in Fig. 8 (d). In addition, the FFT analysis in

Fig. 9 proves that the periodicity elimination of the proposed method is more effective than that of the conventional method. These results show that the performance of the proposed method is greater than that of the conventional method, and verify that the proposed method realizes fine force estimation with the remarkable noise suppression based on the superior wideband and periodicity-cancellation force observer when DOB pole is increased to 6280 rad/s (≈1 kHz).

4.2 *Enhanced force sensation by deep-learning-based adaptive-noise-cancellation force sensing in variable noise conditions*

The performance of the proposed method (DOB with DL based SSA) is verified by experiments of force sensing in the condition of variable noise characteristics. The proposed method is compared with the conventional method using DOB with SSA in which the embedded dimension (M) is a constant of 4.

Fig. 10 illustrates the estimation of the embedded dimension of SSA by the DNN with the square torque command. The result clarifies that the embedded dimension M varies when the noise characteristics change.

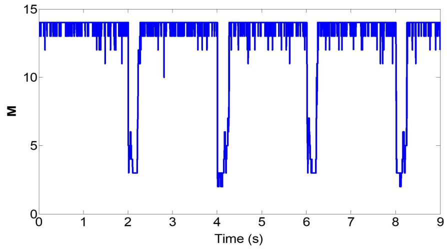

Fig. 10. Embedded dimension estimated by the DNN

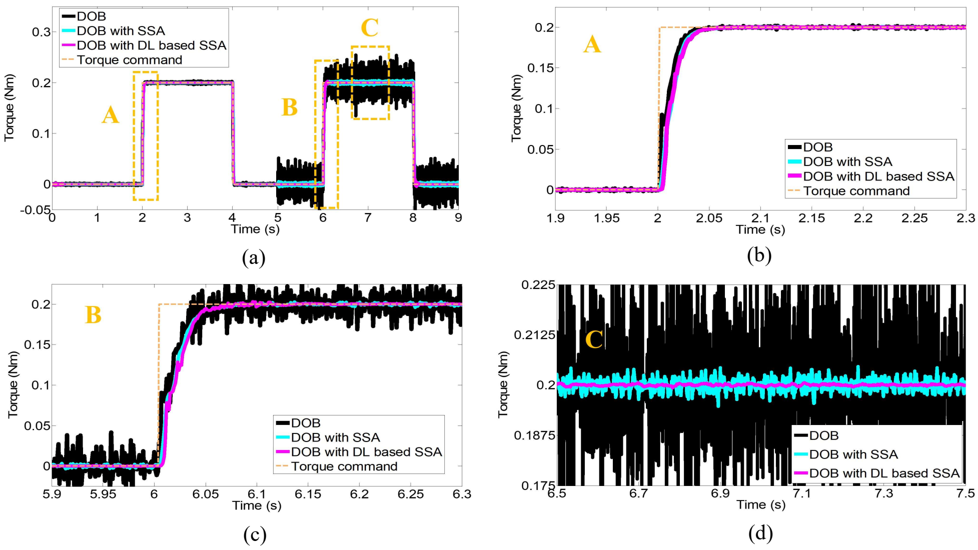

Fig. 11. Force sensing in variable noise condition. (a) Torque estimations. (b) Magnification of A area in (a). (c) Magnification of B area in (a). (d) Magnification of C area in (a)

Fig. 11 presents the experimental results of force sensing with a square torque command in condition of variable noise. The results show that the proposed method and the conventional method (constant M) have similar force sensing performances in the case of low-noise level (Fig. 11 (b)). When the noise changes from low to high level, the transient responses of both methods are almost similar (Fig. 11 (c)). However, in the condition of high-noise level, the remaining noise in the steady state of force estimation using the conventional method (constant M) is still high, while the proposed method achieves the effective noise suppression (Fig. 11 (d)).

The above results verify that using the proposed method, the embedded dimension M of the SSA adapts to the noise variation and the adaptive-noise cancellation in force sensation is realized. With the adaptive-noise-cancellation force sensing, more precise force information is acquired owing to the effective attenuation of variable noise components. Hence, the force sensing performance is significantly improved even in the condition of different SNRs and variable noise characteristics.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　1件）

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３．雑誌名 IEEJ Journal of Industry Applications	６．最初と最後の頁 1-13
掲載論文のDOI（デジタルオブジェクト識別子） 10.1541/ieejjia.22000390	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

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4．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関