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Compressive Feedback for Robot Motion Control ⋆

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Abstract: Robot motion control aims at generating control inputs for a robotic system to track a planned trajectory. Feedbacks provided by sensors play an essential role in motion control by improving the system performance when external disturbances and/or initial errors exist. However, feedback signals, such as images are often of large size, which imposes a heavy computational burden on the system. In this paper, a new robot motion control scheme is proposed based on a low dimensional compressive feedback to increase the feedback rate. The controller is designed in the non-vector space with compressive feedback. As an application, visual servoing is formulated under the proposed framework by considering a feedback image as a set, instead of a traditional feature vector. Experiments are conducted to validate the proposed control scheme.

Keywords: compressive feedback, motion control, visual servoing

1. INTRODUCTION

Robot motion control aims to generate control signals for tracking a planned trajectory of a robotic system. Over the last couple of decades, the research of this technology has made considerable advances with a broad range of applications, such as robotic manipulations in the manufacturing industry, physical surgery in the medical field, target tracking in military, and more recently, the navigation of drones and autonomous vehicles. In a robot motion control system, feedback information plays an important role to improve the system performance by controlling the motion in a closed-loop strategy. Data, such as image and force/torque have been used as feedback information, especially with the development of big data and artificial intelligence. However, the feedback data are often of large size, which decreases the feedback rate and thus reduce the real-time performance of a system. Vision-based motion control is a typical example where the feedback information is often of large size. In order to overcome this issue, a new motion control scheme is proposed based on compressive feedback. Compressive feedback means the feedback data are represented in a compressed form or obtained in a compact form in the acquisition stage. As an application, the proposed method is applied to visual servoing.

Visual servoing aims at controlling the motion of a dynamic system in a closed-loop strategy, using visual information extracted from images provided by vision sensors Chaumette and Hutchinson (2006). A control law is designed to minimize the error which is a function of a set of desired and current visual features to zero. The widely used image features are geometric features, such as image moments Tahri et al. (2015), coordinates of points and orientation of lines in an image. However, these visual servoing methods require complex image processing techniques to generate motion commands. Furthermore, extracting reliable features is of a great challenge in some cases where no explicit features are available, or occlusion and illumination variation exist.

To overcome these drawbacks, some direct visual servoing schemes have been proposed. Instead of using geometric features, these approaches depend on global visual information, such as image intensities Collewet and Marchand (2011), projective homography Gong et al. (2018), trifocal tensor Zhang et al. (2019), image representations based on wavelet Ourak et al. (2019) and shearlet Duflot et al. (2019) transforms. These methods use vectors to represent the visual information, which avoids the feature tracking process. However, these methods impose a computational load on the system because all the redundant image information is considered. Another type of direct visual servoing approaches formulated in the non-vector space has been emerging in recent years. The basic idea of this approach is to treat a feedback image as a set, instead of feature vectors. The goal is to design a controller to minimize the error of two image sets to zero. This approach originated from the work of Doyen (1995). Recently, Zhao et al. (2012) illustrated that the non-vector space control scheme works when only a part of pixel-wise image information is used as feedback. Song et al. (2014, 2018) developed and applied this method to nano-scale motion control. However, this suffers from information loss because only partial image information is considered.

In this paper, a compressive feedback control scheme is proposed in the non-vector space. Comparing with the work of Zhao et al. (2012) and Song et al. (2014), the

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proposed approach provides a more flexible way to acquire the compressive feedback. Besides, the proposed approach allows for global compressive feedback information while they only considered partial pixel-wise image information, which suffers from information loss. In addition, the proposed methods also allows for the design of a specific sensing strategy which is of high performance for a given problem. Note that the proposed method is fundamentally different from the vector-based visual servoing schemes because the controller is designed in the space of sets where the linear structure of the vector space is not applicable. The control error and dynamics are also defined based on sets. Therefore, set-related mathematical tools are needed to describe a system.

The rest of this paper proceeds as follows. Section 2 proposes the compressive feedback control scheme. In section 3, this scheme is applied to visual servoing. In section 4, experimental results are provided to verify the proposed approach. Finally, section 5 summarizes and concludes this paper.

2. COMPRESSIVE FEEDBACK CONTROL

2.1 Problem Formulation

For a dynamical system, define $A \subset R^n$ as the original state space. The compressive state space $B \subset R^m$ is obtained based on the mapping $\phi : A \mapsto B$. Let $x \in R^n$, $y \in R^m$ be the original and compressive state vectors. Their corresponding state sets are defined as $X := \{[x_i, i]^T : i = 1, 2, \dots, n\}$ and $Y := \{[y_i, i]^T : i = 1, 2, \dots, m\}$, where x_i is the i-th coordinate in x, and y_i is the i-th coordinate in y. Here $m < n$, which means compressive feedbacks are of smaller size and this is also why it is called compressive feedback. The goal is to stabilize the initial compressed feedback set Y at the desired set $\hat{Y}$ such that the initial original set X converges to the desired original set $\hat{X}$. In other words, compressive feedback control aims to perform the control of a robot system with the feedback information in the compressive space, but the convergence in the original space can be guaranteed.

2.2 Compressive Feedback Control

In a non-vector space control system, sets are used to describe the state and dynamics of the system. The main question is how to formulate the dynamics of a system. Here, only the core knowledge of non-vector space control framework is provided to be self-contained. The interested readers are referred to the references Song et al. (2014, 2018) for more details.

The distance from a point $\hat{s} \in \hat{Y}$ to a set Y is defined as $d_Y(\hat{s}) = \min_{s \in Y} \|\hat{s} - s\|$ and the projection from $\hat{s} \in \hat{Y}$ to Y is defined as $P_Y(\hat{s}) = \{s \in Y : \|\hat{s} - s\| = d_Y(\hat{s})\}$

To describe the dynamics of a system, a tube and transition need to be defined. A tube is defined as a mapping $Y(t) : R^+ \mapsto P(E)$, where $P(E)$ is a powerset of E. Suppose a mapping $\varphi : E \mapsto R^m$ where $E \subset R^m$ is a Lipschitz function. The set of all the functions is denoted as $BL(E, R^m)$. The transition for φ is defined as

$$T_\varphi(t, Y_0) = \{s(t) : \dot{s} = \varphi(s), s(0) \in Y_0\} \tag{1}$$

Then the derivative of a tube, denoted as $\overset{o}{Y}(t)$ is defined as

$$\overset{o}{Y}(t) = \{\varphi(s(t)) \in BL(E, R^m) : (3) \text{ is satisfied}\}. \tag{2}$$

$$\lim_{\Delta t \to 0^+} \frac{1}{\Delta t} dh(Y(t + \Delta t), T_\varphi(\Delta t, Y(t))) = 0 \tag{3}$$

Hence, the dynamics can be formulated with the following mutation equation:

$$\varphi(s(t)) \in \overset{o}{Y}(t). \tag{4}$$

To take a control signal into the mutation equation, the controlled mutation equation is defined as follows:

$$\varphi(s(t), \xi(t)) \in \overset{o}{Y}(t) \quad \text{with} \quad \xi(t) = \gamma(Y(t)) \tag{5}$$

where $\gamma : P(E) \mapsto \chi$ (χ is a collection of all the possible control signals ξ.) represents the feedback map from the current image set $Y(t)$ to the control input $\xi(t)$.

According to the work of Doyen (1995), if φ in (5) is linear in $\xi(t)$, there is the following theorem:

Theorem 1. For a system described by the following set dynamics:

$$\varphi(s(t), \xi(t)) = L(s(t))\xi(t) \in \overset{o}{Y}(t) \quad with \quad Y(0) = Y_0 \tag{6}$$

where $L(s(t)) \in R^{p \times q}$, $s(t) \in Y(t) \subset R^p$, $\xi(t) \in R^q$ and $\varphi(s(t), \xi(t)) \in BL(E, R^p)$, the following controller can locally asymptotically stabilize it at a desired set $\hat{Y}$:

$$u = \gamma(Y) = -\alpha V(Y) A(Y)^+ \tag{7}$$

where $\alpha \in R_{\geq 0}$ is a gain factor. $V(Y) = \int_Y d^2_{\hat{Y}}(s)ds + \int_{\hat{Y}} d^2_Y(s)ds$ is the Lyapunov function, and $A(Y)^+$ is the Moore-Penrose pseudo-inverse of $A(Y)$ which is a column vector defined as

$$\begin{aligned} A(Y) = \frac{1}{2} \int_Y d^2_{\hat{Y}}(s) (\sum_{i=1}^{p} \frac{\partial L_i}{\partial s_i})^T ds + \int_Y L(s)^T (s - P_{\hat{Y}}(s)) ds \\ + \int_{\hat{Y}} L(P_Y(s))^T (s - P_Y(s)) ds \end{aligned} \tag{8}$$

where L_i is the $i-th$ row vector in matrix L.

3. APPLICATION TO VISUAL SERVOING

In this section, the proposed compressive feedback control scheme is applied to visual servoing. As illustrated in Fig. 1, we aim to move a robot arm from the current position where a compressive current image is recorded to a desired position where a desired image is obtained based on the compressive feedback images. Compressive sensing (CS) is used to obtain the compressive feedback images.

For an image $x \in R^n$, the compressed form $y \in R^m (m \ll n)$ can be obtained based on compressive sensing theory. The compressed image can be represented with the set $Y := \{[y_i, i]^T : i = 1, 2, \dots, m\} \subset R^2$. Φ is used to denote the sensing matrix, and L_x is used to represent the relationship between the time variation of x and the camera's spatial velocity $\xi(t) = (v_x, v_y, v_z, \omega_x, \omega_y, \omega_z)^T$. Then the relationship between the camera's spatial velocity and the

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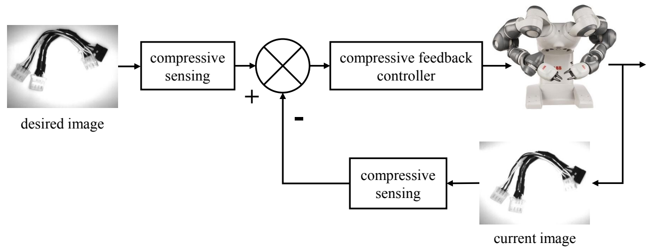

Fig. 1. Control schematic of compressive feedback for visual servoing

time derivative $\dot{s}$ of the elements $s = [y_i, i]^T$ of Y is given as:

$$\dot{s}(t) = L(s(t))\xi(t). \tag{9}$$

where $L(s(t)) = \begin{bmatrix} e(i)\Phi L_x(t) \\ 0 \end{bmatrix}$ and $e(i)$ is a unit vector with the i-th entry be 1 and others be 0.

The dynamics satisfies Theorem 1. Therefore, (7), can be used as the stabilization controller with the compressive feedback.

4. EXPERIMENTAL VALIDATIONS

4.1 Experimental Setup

A collaborative dual-arm robot, YuMi, IRB 14000, from ABB Inc. is used. Each arm has 7 degrees-of-freedom, and a camera is mounted on each end-effector (the eye-in-hand configuration). As the first step, to concentrate on validating the feasibility of the proposed scheme, the experiments on translational motions along x-axis and y-axis are conducted. Images are captured at the rate of 16 frames per second with the size of 480 × 640 pixels. The control law is implemented with Matlab 2015b running on a 64-bit Windows 10 laptop with a 6G memory and a 3.4GHz Intel (R) Core (TM) i7-9400 CPU. The experimental setup is shown in Fig. 2.

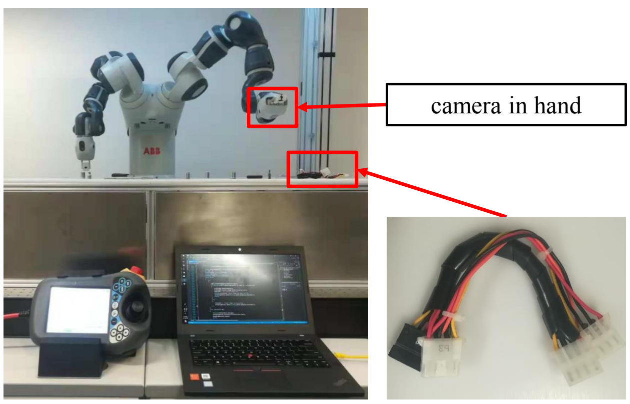

Fig. 2. Experimental setup

For all the experiments, the same random Gaussian matrix whose entries satisfy the standard Gaussian distribution is used to perform compressive sensing, and the sensing ratio is 10%. During the experiments, the robot arm is moved to a desired location and an image is recorded as the desired image. Then the robot is relocated to the initial location which is 10 mm far away from the desired location in both x-axis and y-axis, and an image is obtained as the initial image. These two images are compressed with compressive sensing technology to obtain the compressed images. The non-vector space controller can generate control signals, i.e., camera's velocity, based on the compressed images. It is worth noting that the compressed images are expected to directly obtain by a compressive sensing-based imaging device, instead of capturing the spatial domain image with a traditional CCD or CMOS-based camera. Here we focus on the verification of the proposed control scheme, and thus use a computer to simulate the process of compressive sensing to obtain the compressive images.

4.2 Experimental Results

Partial occlusion condition This experiment aims to validate the performance of the proposed control method when a part of the image is occluded during a visual servoing task. First of all, the robot is moved to a location and a desired image without occlusion is recorded. Then the robot is relocated to the initial position, and a connector is added to hide a part of the cable. During the whole visual servoing task, the connector keeps hiding the same part of the cable. The desired and initial images are shown in Fig. 3 (a), and the experimental results are illustrated in Fig. 4. It can be observed that the controller converges.

Illumination variation condition This experiment deals with the lighting disturbance. The desired image is recorded under the normal condition without occlusion or illumination variation, but the illumination is changed by a lamp during the visual servoing task. As shown in Fig. 5, the controller can still move the robot arm to the desired configuration because the errors in both x-axis and y-axis decreases.

Mixture condition In this experiment, the desired image is obtained in the normal condition, while another cable is added into the field of camera when the robot arm starts moving to the desired position. From Fig. 6, it can be observed that although other cable appears in the image, the controller can still converge to the desired position.

5. CONCLUSION

In this paper, a robot motion control scheme based on compressive feedback is proposed. The compressive feedback can reduce computational load because the employed feedback information is of low size. The controller can generate control signals based on sets in the non-vector space. The proposed approach is applied to visual servoing, and experimental results are provided to validate the approach. The proposed control scheme can be extended to other sensor-based feedback control systems, such as robotic assembly, navigation of drone and autonomous vehicles. In the future, the proposed approach will be implemented on visual servoing in the 3D space where both translational and rotational motions are considered.

REFERENCES

Chaumette, F. and Hutchinson, S. (2006). Visual servo control. i. basic approaches. *IEEE Robotics and Automation Magazine*, 13(4), 82–90.

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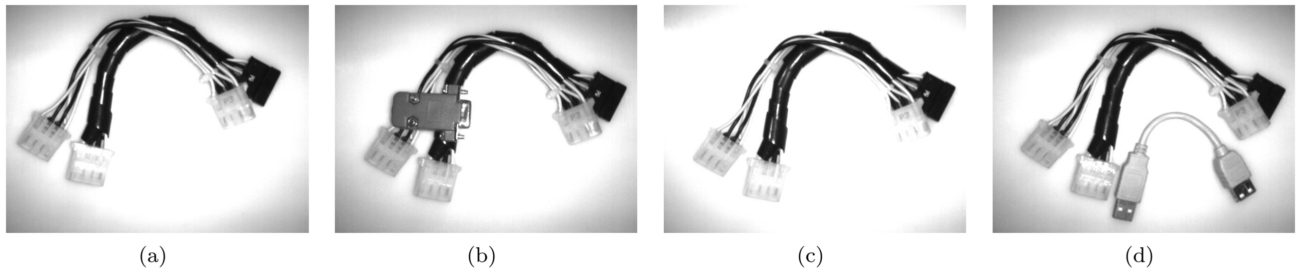

Fig. 3. (a) Desired image under all conditions and initial images under (b) partial occlusion condition, (c) illumination variation condition and (d) mixture condition.

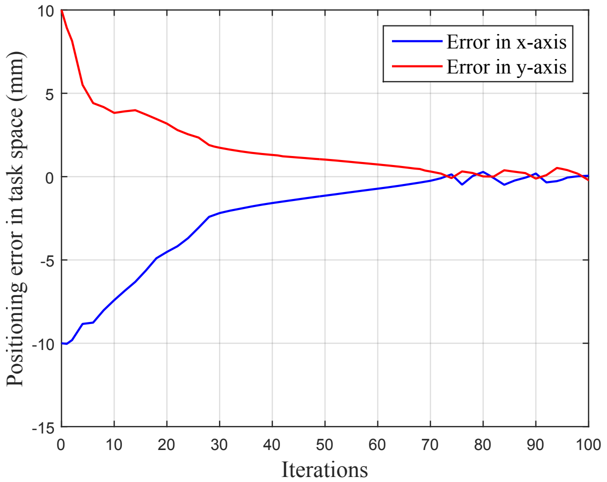

Fig. 4. Error in task space under occlusion condition

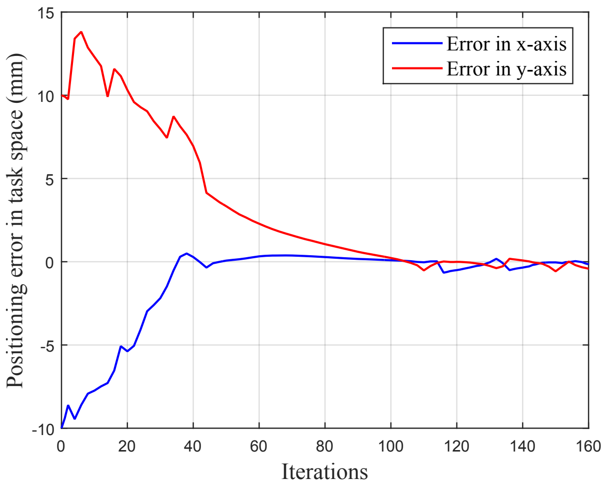

Fig. 5. Error in task space under illumination condition

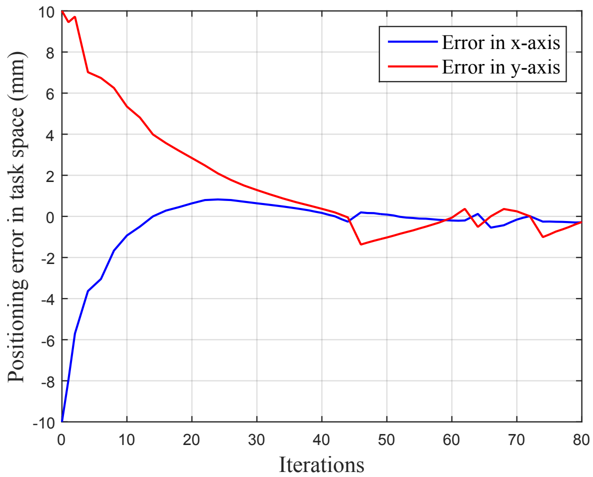

Fig. 6. Error in task space under mixture condition

Collewet, C. and Marchand, E. (2011). Photometric visual servoing. *IEEE Transactions on Robotics*, 27(4), 828–834.

Doyen, L. (1995). Mutational equations for shapes and vision-based control. *Journal of Mathematical Imaging and Vision*, 5(2), 99–109.

Duflot, L.A., Reisenhofer, R., Tamadazte, B., Andreff, N., and Krupa, A. (2019). Wavelet and shearlet-based image representations for visual servoing. *The International Journal of Robotics Research*, 38(4), 422–450.

Gong, Z., Tao, B., Yang, H., Yin, Z., and Ding, H. (2018). An uncalibrated visual servo method based on projective homography. *IEEE Transactions on Automation Science and Engineering*, 15(2), 806–817.

Ourak, M., Tamadazte, B., Lehmaan, O., and Andreff, N. (2019). Direct visual servoing using wavelet coefficients. *IEEE/ASME Transactions on Mechatronics*.

Song, B., Sun, Z., Xi, N., Yang, R., Cheng, Y., Chen, L., and Dong, L. (2018). Enhanced nonvector space approach for nanoscale motion control. *IEEE Transactions on Nanotechnology*, 17(5), 994–1005.

Song, B., Zhao, J., Xi, N., Chen, H., Lai, K.W.C., Yang, R., and Chen, L. (2014). Compressive feedback-based motion control for nanomanipulation—theory and applications. *IEEE Transactions on Robotics*, 30(1), 103–114.

Tahri, O., Tamtsia, A.Y., Mezouar, Y., and Demonceaux, C. (2015). Visual servoing based on shifted moments. *IEEE Transactions on Robotics*, 31(3), 798–804.

Zhang, K., Chaumette, F., and Chen, J. (2019). Trifocal tensor-based 6-dof visual servoing. *The International Journal of Robotics Research*, 38(10-11), 1208–1228.

Zhao, J., Song, B., Xi, N., Lai, K.W.C., Chen, H., and Qu, C. (2012). Compressive feedback based non-vector space control. In *2012 American Control Conference (ACC)*, 4090–4095. IEEE.