Trajectory Control of Manipulator Fed by Power Packets

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Summary

The conventional power supply is based on a continuous flow of electricity. Electrically driven independent systems face the limitations of flexibility and efficiency of power management in a network consisting of power sources, converters, and loads. The power packet dispatching system, where electricity is transferred in a discretized form with information, is expected to remove the limitations. The system realizes a dynamic arrangement of power-line connection between power sources and loads. In this paper, we focus on its application to a manipulator. This is an example of electro-mechanical actuation in independent systems. We verify the trajectory control of the manipulator fed by power packets numerically and experimentally. The results indicate that power packets as a discretized transfer of electricity can be applied to the electro-mechanical actuation.

keywords: power packet; power router; manipulator; trajectory control

1 Introduction

Recently there have been novel studies on electrically driven independent systems, including a highly mobile robot [1], an electric vehicle [2], and a More Electric Aircraft [3]. Their power systems supply power to the loads through power converters connected to a bus power-line. The converters regulate their output to control the current flow.

The conventional power systems will limit flexibility and efficiency of power management in a network consisting of power sources, converters, and loads. In other words, the present systems strongly depend on an assumption that their power sources are large enough to feed every load. However, since independent systems are disconnected from the external power sources, their maximum power is limited at finite. In addition, in order to improve the energy efficiency, many independent systems have recently adopted power sources of time-varying generation profiles (e.g. energy regeneration in [1] and photovoltaics in [2]). It causes a difficulty in keeping the balance of demand and supply. The imbalance may cause the excess or shortage of power supply to the loads. In the worst cases, the loads are damaged or do not operate as expected.

The power packet dispatching system [4, 5] is expected to be a solution for management of the complex interactions between many sources and loads. Figure 1 illustrates the concept of power packet dispatching system. In the system, power and information are transferred simultaneously in the physical layer. Information tags of voltage logic waveforms are attached to direct current (DC) pulse power; the form is called power packet. The tags of each packet include information about the origin and destination of the pulse power. According to the information, power packets are delivered to their destinations through dynamically changing power-line connection between power sources and loads. Each router in the dispatching network contains switching devices,

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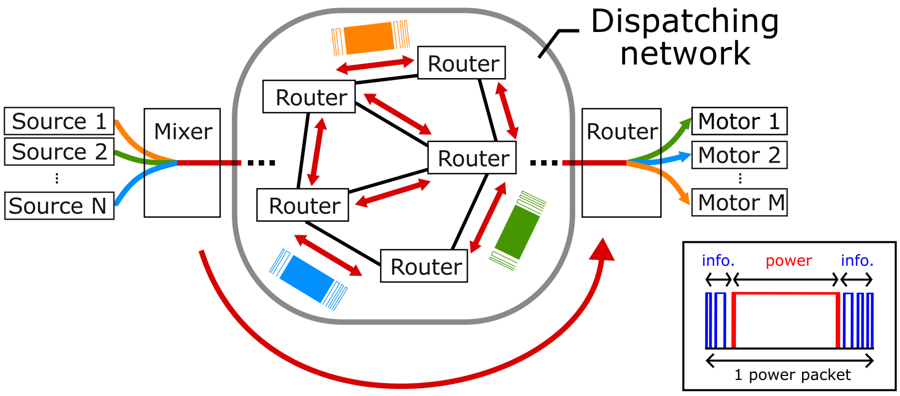


Figure 1: Concept of power packet dispatching.

which realizes the dynamic arrangement of the dispatching paths. The discretization of power and simultaneous transfer of information enable the system to make a distinction of each power packet in the distibution network. Thus, by adopting time division multiplexing (TDM) method for power packet transfer, the system can guarantee that power from different sources is not mixed even when the same power-line is shared for power deliveries among multiple pairs of sources and loads. It indicates that the system has the potential to realize the power supply based on demand and supply between sources and loads.

The concept of power packetization was first introduced by Toyoda and Saitoh in 1990s [6]. They proposed to treat energy in a packetized form in an energy network where many types of dispersed generation plants can generate effectively and participate in a market. However, their proposal was too early to be realized, especitally because of the immaturity in power electronics and information and communications technologies. Besides their proposal, several researches, e.g. [4, 7, 8], have recently proposed power routing in packetized form. Among them, our system shows a distinctive feature in that it realizes power packetization in the physical layer. The realization owes largely to the recent development of wide bandgap power devices; power packets are generated from dc sources by switching in mixers, and the routing of power packets is achieved by circuit switching in routers. Wide bandgap devices enable the high frequency switching without remarkable loss. Our group has already verified power packet routing with networked routers in a laboratory experimental system [5]. The study focuses on the realization of a networked power packet distribution system with proposed routing circuits, not on the control of loads with the dispatching system.

As an application of the power packet dispatching to independent systems, we have studied the possibility of the motion control by power packets [9, 10]. In the power packet dispatching system, the amount of transferred power can be estimated by the number of packets supplied in a given time period [11, 12, 13, 14]. In other words, the power supply is discretized by an intermittent supply of power pulses. Our previous study [10] numerically verified that power packets can supply requested power to electric motors for manipulation. In the study, we adopted a density modulation of power packets using dynamic quantizer [11, 12, 15]. Several power electronics applications, e.g. a light dimming [16], also adopt a pulse density modulation for power regulation. Among them, our proposal can realize the simultaneous transfer of power and information in each power pulse.

In this paper, we discuss the feasibility of the motion control by power packets. First, the trajectory control is verified by an experiment with a scheme of the packet supply simplified from the previous method in [10]. The scheme does not use the system models explicitly. Then we also confirm the validity of numerical models of the experimental system as an estimation of input-output relation for model-based control schemes. This is assessed in a comparison between numerical simulation and experimental results.

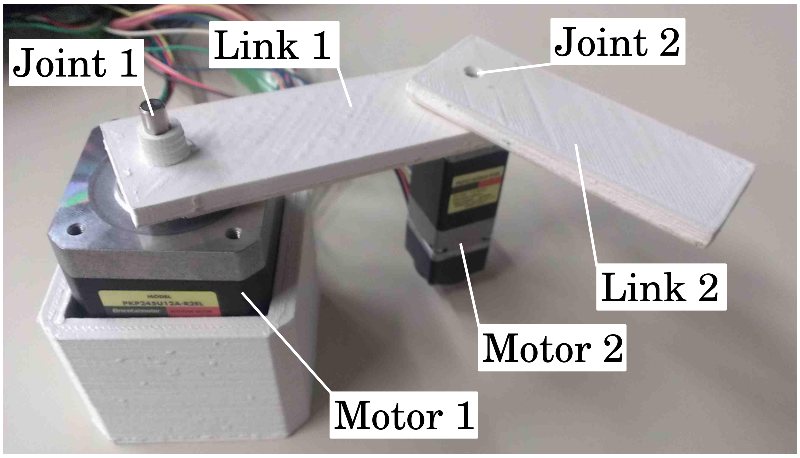


Figure 2: Photograph of manipulator used in experiment.

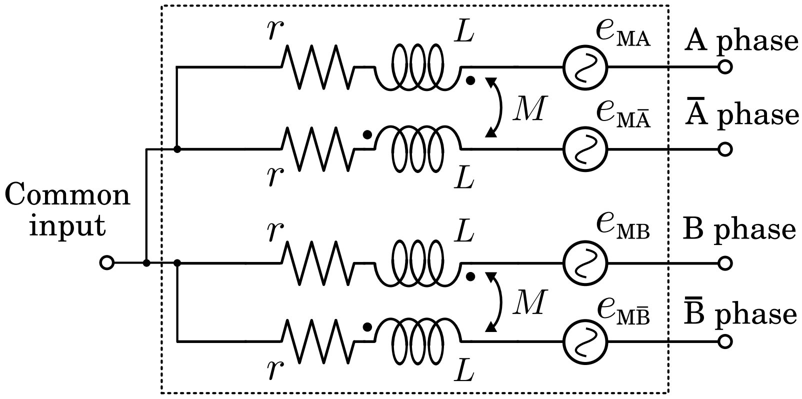


Figure 3: Electrical circuit of stepper motor.

2 Manipulator and Driving Circuit with Power Packet Dispatching

2.1 Configuration of manipulator

A simple planer manipulator is adopted as a system of two degrees of freedom. The experimental setup is shown in Fig. 2. It consists of two links which are driven by two motors at the joints. The independent set of generalized coordinates are defined by θ_1 and θ_2, which are the rotation angles of motor 1 at joint 1 and motor 2 at joint 2, respectively. Dynamic equations in terms of displacements θ_1 and θ_2, and joint torques τ_1 and τ_2 are given as follows[17]:

$$\tau_1 = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 + h_{122}\dot{\theta}_2{}^2 + h_{112}\dot{\theta}_1\dot{\theta}_2 + c_1\dot{\theta}_1, \quad (1)$$

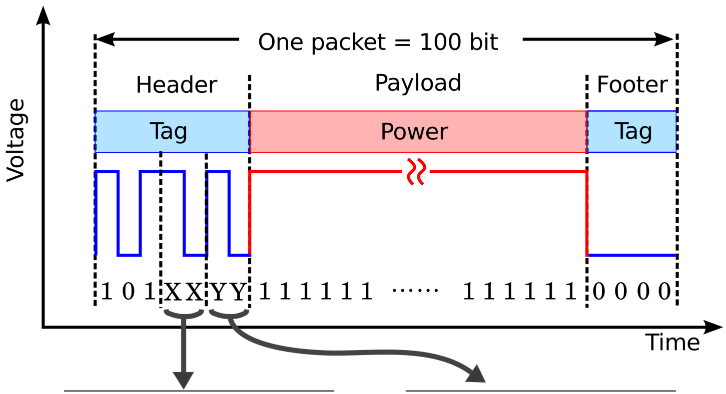
$$\tau_2 = H_{21}\ddot{\theta}_1 + H_{22}\ddot{\theta}_2 + h_{211}\dot{\theta}_1{}^2 + c_2\dot{\theta}_2, \quad (2)$$

where coefficients H and h are functions of θ_2, and c is a friction constant.

Unipolar hybrid-type stepper motors are placed at the joint of two links. Each motor has two complementary pairs of excitation phases and are modeled by the equivalent circuit shown in Fig. 3. The circuit equation for A phase in terms of input voltage V_A and current i_A, $i_{\bar{A}}$ is given as follows:

$$V_A - ri_A - L\frac{di_A}{dt} + M\frac{di_{\bar{A}}}{dt} + e_{MA}(\theta, \omega) = 0, \quad (3)$$

where r, L, and M denote a resistance, an inductance, and a mutual inductance of a motor winding, respectively. The term e_{MA} represents a back electromotive force of phase A, which is a function of the motor angle θ and angular velocity ω. Stepper motors rotate when current sequentially flows through the phases in an appropriate order. The current produces the rotation torque τ as given by



Destination motor	X X
Motor 1	1 0
Motor 2	1 1
None	0 *
(* represents "don't care")	

Destination phases	Y Y
A and B	0 0
B and $\bar{A}$	0 1
$\bar{A}$ and $\bar{B}$	1 0
$\bar{B}$ and A	1 1

Figure 4: Configuration of power packet.

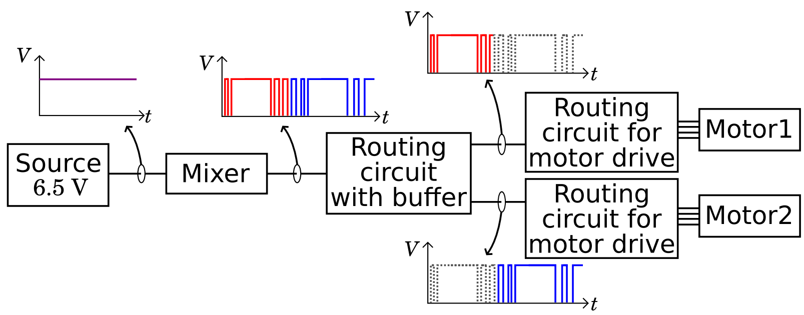


Figure 5: Configuration of dispatching circuit.

the following equation:

$$\tau = -pK_e(i_A - i_{\bar{A}}) \sin p\theta - pK_e(i_B - i_{\bar{B}}) \sin p(\theta - \lambda), \tag{4}$$

where p, λ and K_e denote constants determined by the structure and magnetic characteristics of the motors.

2.2 Power Packet and Its Dispatching Circuit

In the power packet dispatching system, electric power is divided into a sum of discretized units shown in Fig. 4, which are called power packets. A power packet is composed of a payload and an information tag. The payload is a pulse-shaped dc power. The information tag, composed of a header and a footer, is attached by voltage logic waveforms without current. In this paper, the whole packet consists of 100 bits, and the length of each packet is set at 2^{13} μs (about 8.2 ms). Power packet is composed of 7 bits as a header, 89 bits as a payload (its all bits are "1"), and 4 bits as a footer, as shown in Fig. 4. The header includes four bits to identify a destination of the packet. Of course, there are other configurations available for composing a packet; the most important point is the simultaneous transfer of the payload and the tag.

We consider a power packet dispatching system for the manipulator shown in Fig. 5. It contains a dc voltage source set at 6.5 V, a mixer, a routing circuit with buffer (RCB), two routing circuits for motor drive (RCMDs), and two stepper motors. Figure 6 depicts the configuration of the mixer. The mixer generates a train of power packets from the voltage source by switching. The packets are sent to RCB depicted in Fig. 7. It reads the information written in the header and forwards the

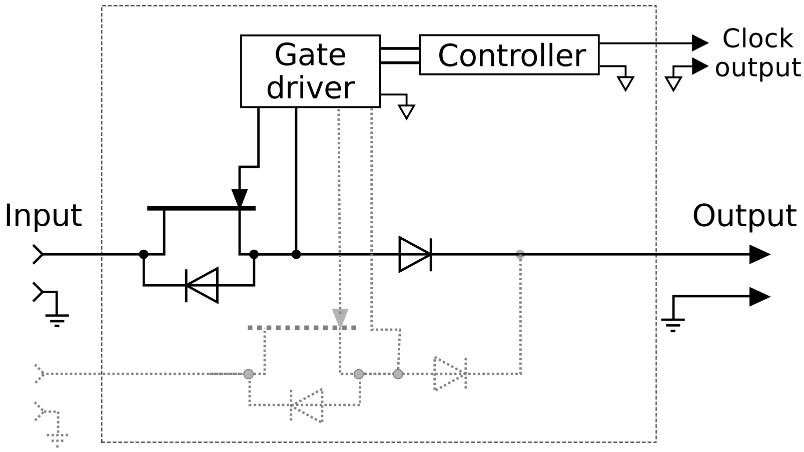


Figure 6: Configuration of power mixer. Only one input port is used here.

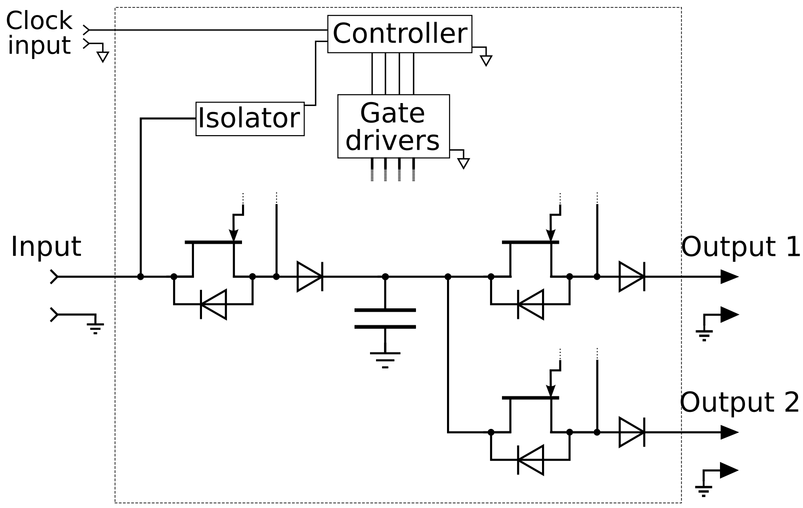


Figure 7: Configuration of routing circuit with buffer (RCB).

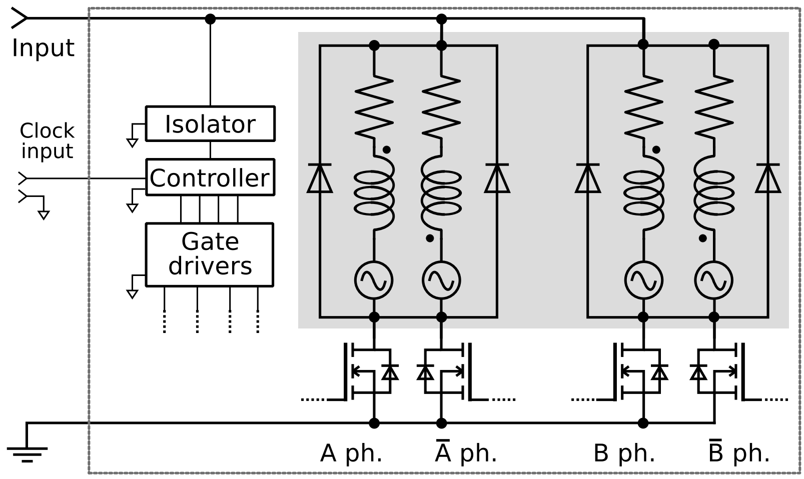


Figure 8: Configuration of routing circuit for motor drive (RCMD) proposed in [9].

packet to the desired destination, or one of the RCMDs, according to the information. Figure 8 depicts the schematic of RCMD, which was proposed in [9]. RCMD manages four switches, each of which excites the corresponding phase of the motor. The controller of RCMD selects the switches for the requested excitation phases according to the header information of each packet.

Note that, in order to transfer information in tags of power packets correctly, an accurate clock synchronization between the routing apparatuses is necessary. In the prototype system used in this paper, controllers of the mixer, RCB, and RCMDs are connected by external clock lines apart from power-lines. On the other hand, our group has also proposed an autonomous clock synchronization method without any additional lines [18].

3 Trajectory Control of Manipulator

3.1 Packet Generation Procedure

The motors of the manipulator are fed by sequences of power packets. In this system, the control of loads is achieved by the appropriate assignment of destination address in the information tag; the tag determines the spatial-temporal distribution of power packets. The algorithm to generate a power packet operates at the clock period, T_{packet}. The period corresponds to the packet length, which is uniquely fixed for all packets in this paper.

In kth period ($kT_{\text{packet}} \leq t < (k+1)T_{\text{packet}}$), the controller in the mixer determines the destination of the power packet that will be produced in the next period ($(k+1)T_{\text{packet}} \leq t < (k+2)T_{\text{packet}}$). The destination is determined on the basis of given reference trajectories of motor angles, $\theta_{\text{ref}}(t)$, in an open-loop manner. In this paper, we limit the destination of a single power packet only to one of the motors. This limitation is for confirming that the power packetization enables the system to distinguish every transfer of a power packet between a pair of a source and a load. The detail of the algorithm is as follows:

1. reference trajectories in angle at the time, $\theta_{\text{ref}}(kT_{\text{packet}})$, are given to the controller. (In this paper, the reference trajectories are defined in advance. The reference trajectories are defined by displacements from the initial angles of the motors $\theta(0)$.)

2. difference between the reference and estimated angles, $D := \theta_{\text{ref}}(kT_{\text{packet}}) - \theta(kT_{\text{packet}})$, is calculated for each motor. (Note that the motors are stepper motors. We can estimate the present angles by counting the number of transitions of target excitation phases.)

3. target rotation direction of each motor is determined: θ_{step} in clockwise direction if D is greater than $\theta_{\text{step}}/2$, θ_{step} in anticlockwise if D is less than $\theta_{\text{step}}/2$, or no rotation otherwise.

4. target excitation phases of each motor at the next time period is determined according to the rotation direction.

5. the controller selects one of the two motors to be fed in the next period. The target motor is alternately selected; i.e., the motor that did not obtain a power packet at the previous period is selected.

6. destination of a power packet is set by "the motor selected in step 5. and its phases determined in step 4."

The alternation method satisfies the demand from two motors at the same time with sufficiently higher frequency in producing power packets than the mechanical time constant of the manipulator. Our experimental system achieves the required frequency using wide bandgap semiconductor devices [19, 20].

The power feeding scheme above sets a limitation on the amount of power supply per load. When the number of loads in a system increases, the average power available in each load decreases. This is because a single power-line is shared by all power packets of different destinations between the mixer and the RCB. In such a case, a possible solution of the limitation is to prepare multiple routing paths instead of the single path. It can be achieved by setting a routing network consisting of multiple RCBs.

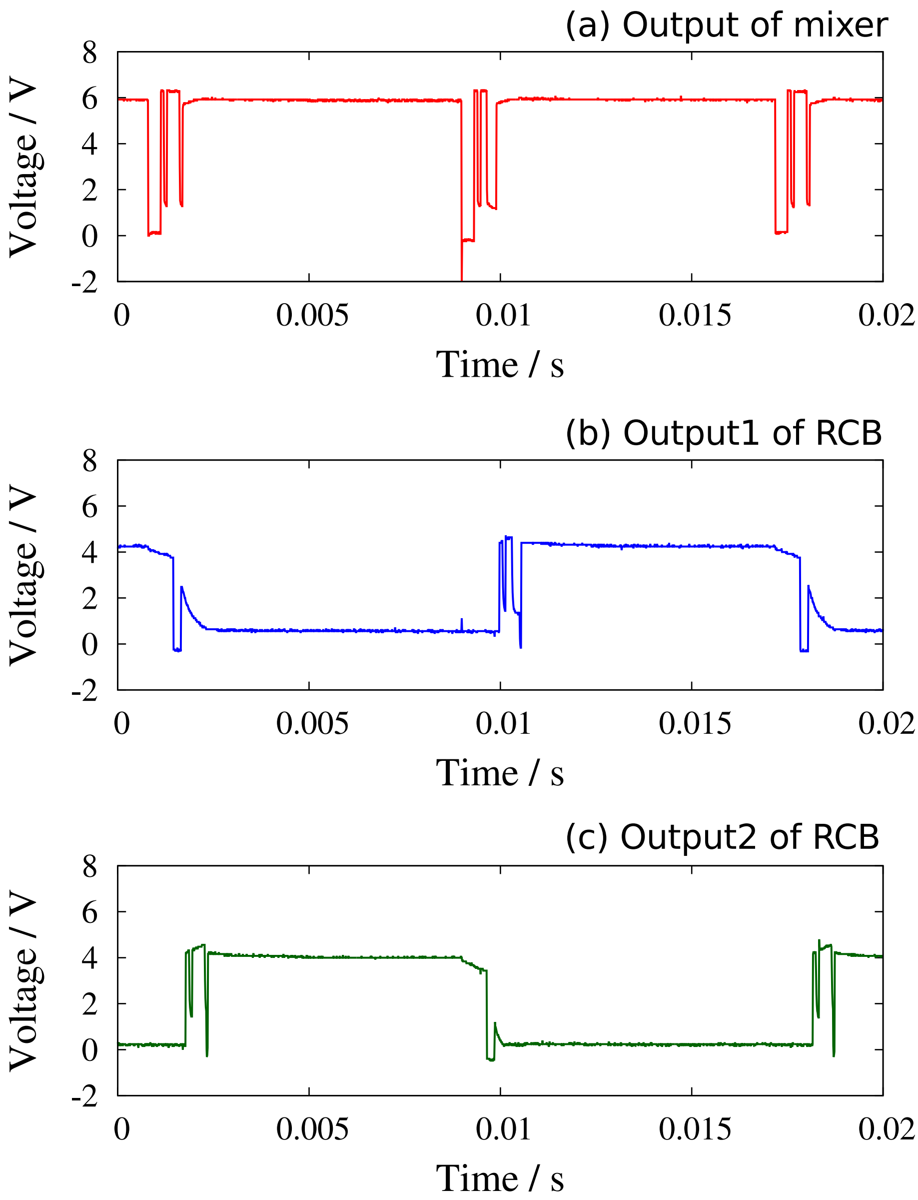


Figure 9: Voltage waveforms of power packets measured in experiment: (a) output of mixer, (b) output 1 of RCB for motor1, and (c) output 2 of RCB for motor 2.

3.2 Experimental Verification of Trajectory Control

In this subsection, we experimentally confirm the achievement of trajectory control by power packets. We assemble the manipulator, dispatching system, and control scheme explained above.

First, we confirm the achievement of the packet transfer by RCB. Figure 9 shows the voltage waveforms measured at (a) output of the mixer, (b) output 1 of RCB (to motor 1), and (c) output 2 of RCB (to motor 2). The figure indicates that power packets produced by the mixer were distributed to the two RCMDs as requested. The packet with the header starting with "10111" was transferred to the output 2 (to motor 2). Then the next packet with the header starting with "10110" was transferred to the output 1 (to motor 1).

Second, we confirm that the RCMDs dispatched the input packets to motor phases as requested. Figure 10 shows the measured current waveforms of motor windings and their target phases. Note that it shows the difference between current waveforms of complementary phases, $i_{\mathrm{A}} - i_{\bar{\mathrm{A}}}$. The positive value represents the excitation to phase A, and the negative to phase $\bar{\mathrm{A}}$. The figure indicates that the input packets generated current pulses in target phases. We also obtained the similar results in phases B and $\bar{\mathrm{B}}$. The results imply that the power packets are dispatched as desired.

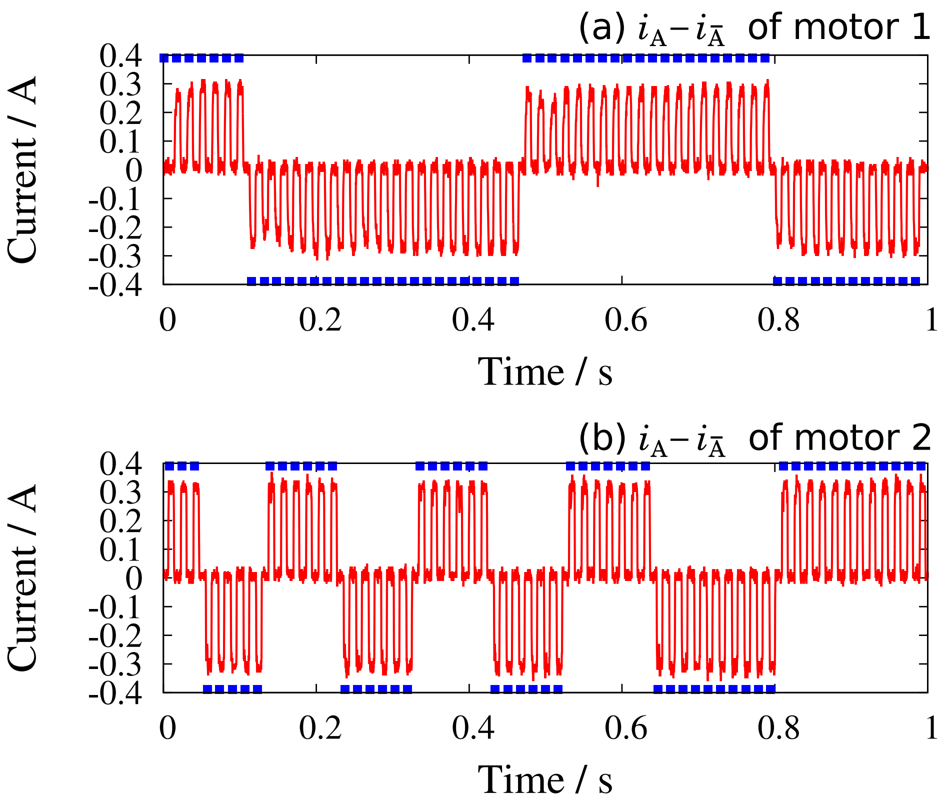


Figure 10: Excitation current waveforms measured in experiment: (a) $i_A - i_{\bar{A}}$ of motor1, and (b) $i_A - i_{\bar{A}}$ of motor 2. Requested excitation phases are also depicted by blue dotted lines. Note that the positive or negative value of the reference represent A phase and Ā phase, respectively.

Lastly, we examine the trajectories of the two motors in angle. Figure 11 shows the measured and reference trajectories. The measured trajectories followed the references as they rotate by step angle, θ_{step} =1.8 °. The intermittent power supply by power packets successfully controlled the trajectories of two motors. This is because the period with no packet supply was sufficiently shorter than the mechanical time constant of the manipulator (approximately 10 ms).

3.3 Numerical Simulation for Validity Verification of System Models

Here we discuss the validity of the system models through numerical simulation. The setup for the simulation is same as the one in the experiment, and equations (1)–(4) are used as numerical models. We referred specifications provided by manufacturers for some parameters of the models, and estimated by experimental measurements for others. We adopt the same scheme of power packet generation as in the experiment, and we assume that all power packets are correctly transferred to the requested destination phases. The results of the simulation are compared with the experiments above.

Figure 12 shows the excitation current waveforms obtained by the simulation, which is overlapped on the experimental results already shown in Fig.10. The figure indicates that the simulation results are consistent with the ones measured in the experiment both in transient and steady state. Figure 13 shows the comparison of angle trajectories obtained by the simulation and the experiment. The angle trajectories of the simulation exhibit the mechanical response to the current inputs similar to the experimentally measured.

These results verify the validity of the system models as an estimation of the experimental system in the mechanical and electrical behavior. Such models are essential for an experimental installation of model-based control schemes with power packets, e.g. an optimal dynamic quantizer proposed in [15]. The adoption of these methods is expected to improve the regulation of instantaneous power with power packets [10, 11].

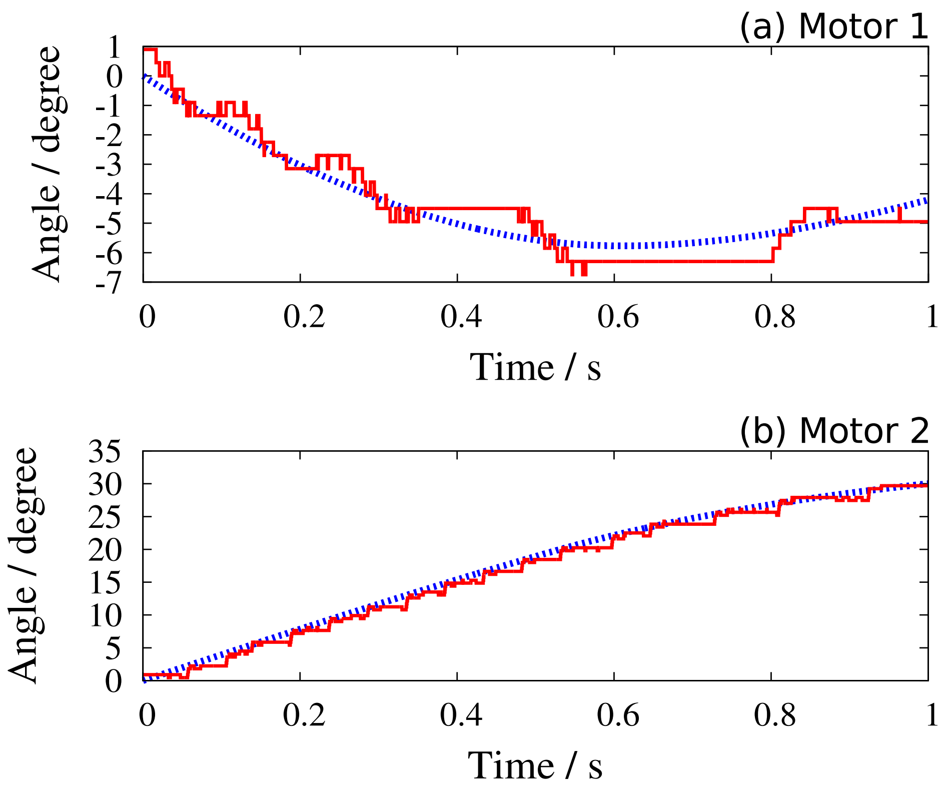


Figure 11: Angle trajectories of motors measured in experiment: (a) motor1, and (b) motor 2. Red solid lines and blue dotted lines represent angle trajectories and their reference trajectories, respectively.

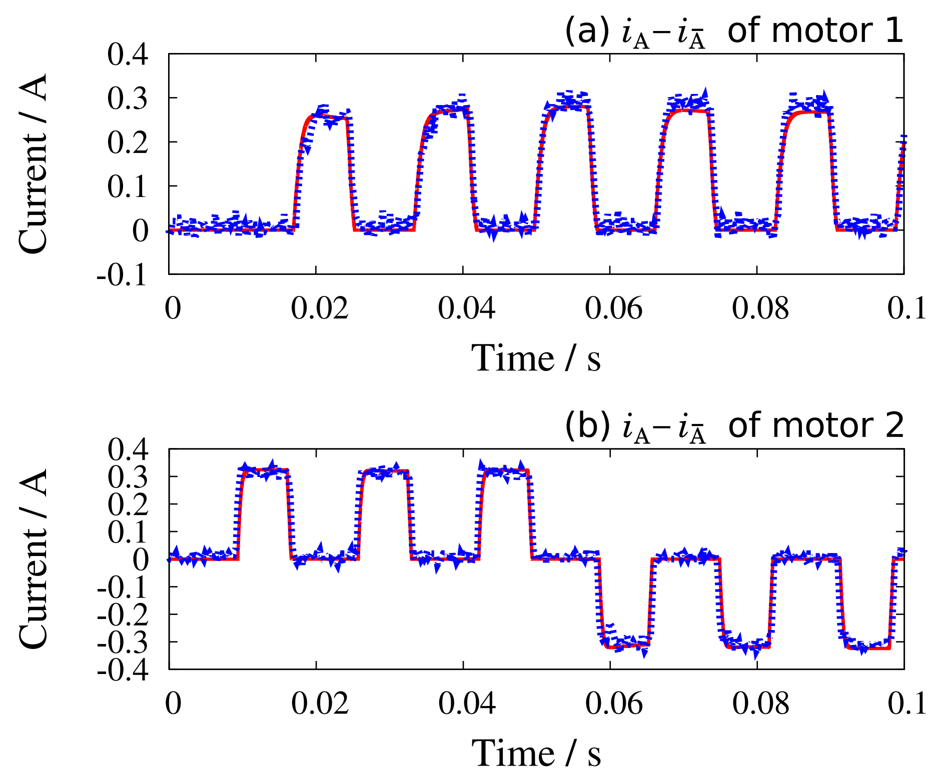


Figure 12: Comparison of current waveforms obtained by simulation (red solid lines) and experiment (blue dotted lines): (a) $i_{\mathrm{A}} - i_{\bar{\mathrm{A}}}$ of motor1, and (b) $i_{\mathrm{A}} - i_{\bar{\mathrm{A}}}$ of motor 2. The waveforms of experiment are enlarged views of the ones in Fig. 10.

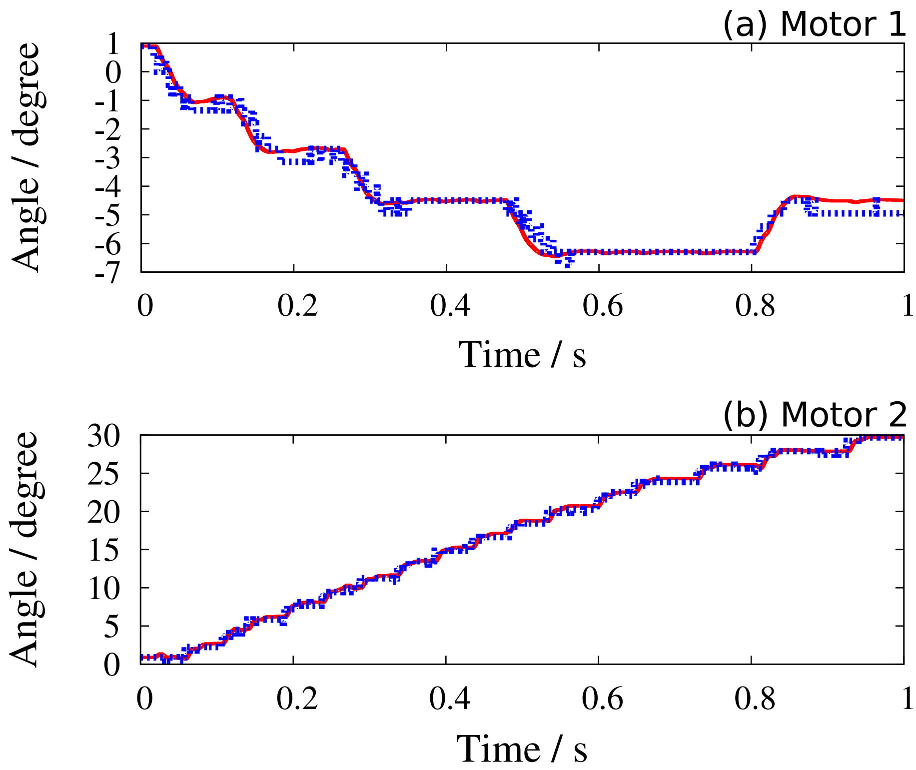


Figure 13: Comparison of angle trajectories obtained by simulation (red solid lines) and experiment (blue dotted lines): (a) motor1, and (b) motor 2. The trajectories of experiment are the same ones as in Fig. 11.

4 Conclusions

In this paper, we discussed the trajectory control of a manipulator fed by power packets. Through the experiments, we confirmed that the discretized power supply through power packets is able to control electro-mechanical systems. In addition, we verified the validity of the numerical models as an estimation of the experimental system. The results suggest the feasibility of motion control by power packets in a real system. The power packet dispatching is expected to be more functional than equivalent continuous system for power management between multiple sources and loads in electrically driven independent systems.

Acknowledgments

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