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Research on the Synergetic Algorithm of Linear Permanent Magnet Motor

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Abstract. This paper studies the motion control system formed by three permanent magnet synchronous linear motors. In order to achieve the coordinated position control of the motors, the author first studies the influence of different communication topologies on the synergetic performance among motors; secondly, the author proposes an adjacent deviation coupled synergetic algorithm to improve the overall control effect of the synergetic system; lastly, the author designs and implements control experiment, the results of which indicate adjacent deviation coupled algorithm can effectively improve the synergetic accuracy among linear motors. Compared with traditional methods, the synergetic error among motors has declined from 0.3 mm to 0.25 mm and the synergetic accuracy has been improved by 17%.

Keywords: adjacent deviation coupled algorithm, communication topology, permanent magnet linear motor

1 Introduction

A large number of high-precision linear cooperative motions are required in modern industrial fields, such as component processing and component assembly. That how to achieve fast and high-precision linear cooperative motion is an urgent problem to be solved in industrial processing assembly process [1-2]. The traditional linear motion is realized by rotating electric machine with additional mechanical transmission mechanisms (such as speed bumps, ball rollers, etc.). In industrial production, it is more inclined to use a direct-drive linear motor to drive the load to realize the linear motion of the mechanism.

Because of its own motion characteristics, linear motors do not need additional mechanical devices (such as gear racks, synchronous belts, etc.), which can reduce the complexity of the mechanical structure of the system and also avoid accumulated errors caused by intermediate links, achieving precise positioning. Thanks to the reduction and omission of the mechanical conversion device, the direct drive system consisting of a linear motor can reduce unnecessary wear and tear, so the linear motor features less mechanical failure and long operating life [3-4].

In the traditional multi-station processing platforms, the actuators operate independently and are only responsible for completing their own processing steps, the information interaction between different actuators fails to realize. As long as there is a positioning deviation, delay or shutdown in any processing step, it will affect the normal operation of other processes, resulting in a decrease of good products and even cause system failure.

PMSLM requires the execution agencies of each process to coordinate and work together to achieve precise positioning and operation. Each of these actuators is regarded as an independent unit of work. In

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addition to obtaining its own state information, it also needs to receive state information from other machines through local communication. Finally, it issues control commands through autonomous operations and works together with other machines. The cooperative working mode enables multiple actuators to be coupled and connected with each other, which can enhance the stability of the entire system as well as improve the production efficiency. Therefore, it's of great significance to research on the cooperative control of multiple linear motors to spread the application of linear motors in industry.

The PMSLM with simple mechanical structure and large thrust density has characteristics of fast response, small volume and light weight, and it has got much attention in industry and academic fields [5-8]. In this essay, the author took the cooperative motion system composed of 3 PMSLMs as research object and carried out the experimental research on multi-motor cooperative control, which goals to improve the position coordination precision of multiple motors during operation. The research includes four aspects as following: the design of fuzzy proportional-integral-derivative (PID) controller with parameter self-tuning function; and construction of multiple-PMSLM synchronous motion system based on RT-LAB (name of commercial controller) platform; the analysis and research of the influence of different communication topologies on the cooperative control performance of multi-linear motors; the experimental research and the result analysis of the adjacent cross-coupling cooperative algorithm. In this essay, a cooperative motion system based on three permanent magnet synchronous linear motors is built on the RT-LAB simulation platform, and the fuzzy PID controller is applied to improve the tracking accuracy of a single motor. The comparison of the influence different communication topologies on the multiple motors is presented. The adjacent cross-coupling cooperative algorithm is proposed to improve the synergy between multiple motors.

2 Mathematical Model

In order to simplify the analysis of the PMSLMs, assumptions are usually made as following: the effects of magnetic circuit saturation, eddy current and hysteresis are ignored; the current flowing into the motor is a symmetric three-phase sinusoidal current; the three-phase stator windings are star-shaped distribution and symmetric in space, the number of turns, resistance and inductance of each phase winding are the same; the magnetomotive force of the permanent magnet of the motor is constant.

It's fact that the system consisting of a PMSLM is a multivariable nonlinear time-varying system, in the analysis and research, the CLARK transformation and the PARK transformation are frequently used to establish the model of the PMSLM in the synchronous rotation coordinate, thus adjusting the torque component and the excitation component seperately [9-10].

After CLARK transformation and PARK transformation, the stator voltage balance equation of the PMSLM can be expressed in synchronous rotating coordinate system as follows:

$$u_d = Ri_d + L_d \frac{di_d}{dt} - \frac{\pi}{\tau} vL_q i_q \quad \textbf{(1-1)}$$

$$u_q = Ri_q + L_q \frac{di_q}{dt} + \left(L_d i_d + \varphi_f\right)\frac{\pi}{\tau} v \quad \textbf{(1-2)}$$

Where τ is the linear motor pole-pitch; φ_f is the coupling of the mover magnetic chain on the stator; v is the moving speed of the mover; R is the coil winding resistance. The electromagnetic thrust equation of the motor can be expressed as follows:

$$F_{em} = \frac{3}{2}\frac{\pi}{\tau}\left[\varphi_f + \left(L_d - L_q\right)i_d\right]i_q \quad \textbf{(1-3)}$$

Assume that $i_d=0$, the formula above can be rewritten as:

$$F_{em} = \frac{3}{2}\frac{\pi}{\tau}\varphi_f i_q \quad \textbf{(1-4)}$$

In the synchronous rotating coordinate system, the motion equation of the PMSLM is:

$$F_{em} = F_d + Bv + M\frac{dv}{dt} \tag{1-5}$$

3 Design of the Controller

In the coordinated motion system composed of multiple linear motors, the running performance of a single motor directly affects the overall cooperative precision of the system. For the nonlinear and time-varying characteristics of permanent magnet synchronous linear motors, the fuzzy PID controller with parameters self-tuning is designed based on the fuzzy principle. The algorithm can adjust the parameters of the controller online while the system is running, improving the position accuracy of the single motor motion system.

Fig. 1 is a system block diagram of a fuzzy PID controller. In the design, the position error and position error rate of the motor are used as reference input, and a series of operations such as fuzzification, fuzzy reasoning and defuzzification are sequentially obtained to obtain appropriate ΔK_p 、 ΔK_i and ΔK_d , and then the corresponding parameter of PID is obtained according to formula (2-1) [11-12].

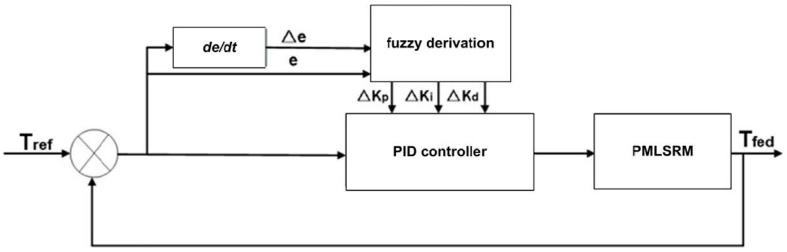


Fig. 1. Fuzzy PID controller system block diagram

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{cases} \tag{2-1}$$

K_{p0} 、 K_{i0} and K_{d0} are the initial parameters of the PID controller.

The reference input variable selects the position error E and the position error change rate ΔE , and the actual output variable selects the controller parameters ΔK_p , ΔK_i and ΔK_d .The domain of the reference input and the actual output are determined as $[-6,6]$; the actual range of the position error and the position error change rate of are $[-5,5]$ and $[-100,100]$ respectively; the actual value ranges of the output variables ΔK_p 、 ΔK_i and ΔK_d are $[-4,4]$, $[0,0]$, $[-0.015,0.015]$ respectively.

The range of reference input and reference output is divided into 7 fuzzy sets: positive big (PB), positive medium (PM), positive small (PS), zero (ZE), negative big (NB), negative medium (NM) and negative small (NS), The membership functions assigned by the fuzzy sets of the variables are all triangles, and the fuzzy rules of the tuning are shown in Table 1.

After the fuzzy rules are formulated, the controller performs fuzzy reasoning based on the established rules to solve the set of output variables. The calculation of fuzzy implication relation adopts minimal operation, while the calculation of rule synthesis relationship selects maximal operation, the system reasoning method is set to Mandani reasoning method, while the defuzzification method is set as center of gravity method.

Table 1. Fuzzy rules

		E						
		NB	NM	NS	ZE	PS	PM	PB
Δ*E*	NB	PB NB PS	PB NB NS	PM NM NB	PM PM NB	PS NS NB	ZE ZE NM	ZE ZE PS
	NM	PB NB PS	PB NB NS	PM NM NB	PS PS NM	PS NS NM	ZE ZE NS	NS ZE ZE
	NS	PM NB ZE	PM NB NS	PM NS NM	PS PS NS	ZE ZE NS	NS PS NS	NS PS ZE
	ZE	PM NB ZE	PM NM NS	PS NS NS	ZE ZE NS	NS PS NS	NM PB NS	NM PB ZE
	PS	PS NM ZE	PS NS ZE	ZE ZE ZE	NS NB ZE	NS PS ZE	NM PB ZE	NM PB ZE
	PM	PS ZE PB	ZE ZE PS	NS PS PS	NM PB ZE	NM NM ZE	NM PB PS	NB PB PB
	PB	ZE ZE PB	ZE ZE PM	NM PS PM	NM PB PS	NM NM PS	NB PB PS	NB PB PB

4 Experimental Study

The author selects 3 PMSLMs produced by Mata Intelligent Technology Co., Ltd. as the controlled object. The specific parameters are shown in Tab. 2. The target lower position machine OP5600 of the semi-physical simulation RT-LAB platform is used as the controller of the motion system. The position sensor MSK200-1 with a rate of 0.001 mm is used as the system feedback component, and the CDHD-006-2A driver produced by Gaochuang Transmission is used to supply current to the motor. The driver is powered by 220V single-phase AC voltage, and the maximum output current is 25.5 A with a frequency response of 3-5 kHz. The multi-PMSLM synchronous control system is shown in Fig. 2.

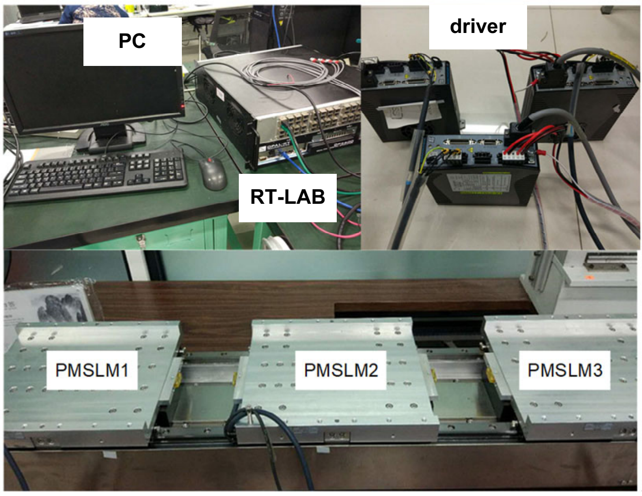


Fig. 2. Multi-PMSM synchronous control system

Table 2. PMSLM specific parameters

Parameter	value	Unit
Pole-pitch	32	mm
Mover mass	0.5	Kg
coil winding inductance	26.7	mH
coil winding resistance	2.6	Ohm
Moment constant	67.8	Nm/A
Continuous thrust	180	N
Dynamic current	5.6	A
Peak point current	16.9	A

After the multi-PMSLM synchronous motion platform is built, the position tracking research of a single motor was carried out first. The position tracking experiment was carried out around both conventional PID controller and fuzzy PID controller. For the convenience of comparative analysis, the tracking reference signals of the two sets of experiments are sinusoidal signals of the same amplitude and the same frequency, with an amplitude of 30 mm and a frequency of 0.2 Hz. Meanwhile, the sampling period of the RT-LAB simulator is set to 0.0001 s. Through trial and error, it is determined that the conventional PID controller parameters are K_p=8 、K_i=0 and K_d=0.015, which also are the initial input parameters of the fuzzy PID controller.

It can be seen from Fig. 3 that when a conventional PID controller is used, the maximum tracking error of a single motor is 0.4 mm; when a fuzzy PID controller is used, the absolute tracking error of a single motor is limited to about 0.3 mm, with the error reduced by nearly 25%. It is superior to the performance when using the conventional PID controller, which shows the superiority of the fuzzy PID controller dynamically adjusting the operating parameters during the operation.

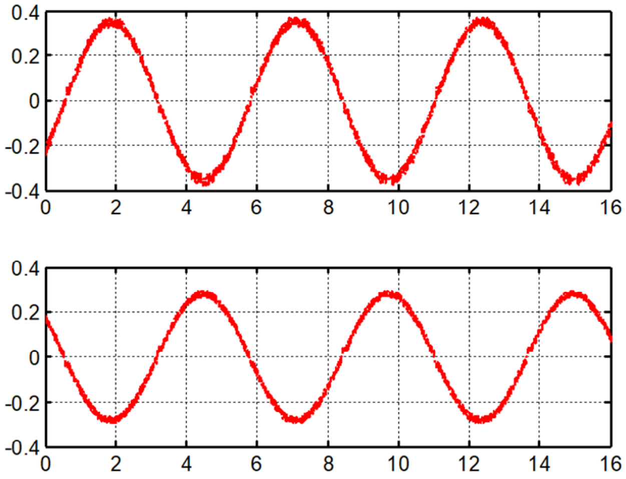


Fig. 3. Conventional PID and fuzzy PID tracking error

4.1 Topology Research Experiment

The topology of the collaborative system directly affects the overall cooperative precision of the collaborative control system. In this essay, the experimental research on the position coordination of multiple-PMSLMs under different topologies is carried out, and the influence of topology on the overall cooperative performance of the motion system is analyzed. Each motor in the collaborative control network can be regarded as a separate node, the nodes exchange their state information (position, speed) between each other by the local communication, and finally according to the information of itself and the peripheral nodes to calculates the corresponding control amount through the built-in control algorithm, completing the state control of itself, as shown in Fig. 4.

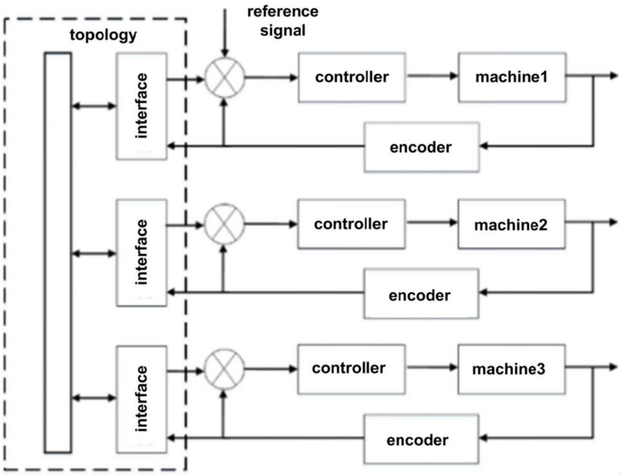


Fig. 4. Multiple PMSLM cooperative control schematic

Multiple motor nodes can form different communication topologies, and the communication topology directly affects the overall performance of the multi-motor synchronous control system [13]. Fig. 5 shows two typical communication topologies, a chain topology and a tree topology. The arrow indicates the flow direction of the motor information.

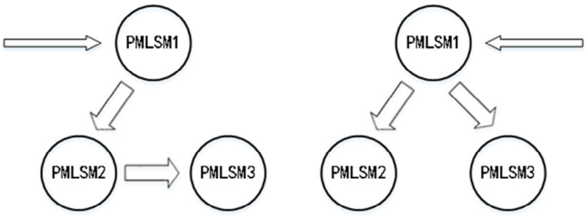


Fig. 5. Chain topology and tree topology

In order to test the dynamic response of the chain topology and the tree topology, a multi-linear motor cooperative motion system composed of either topology is input with the same position reference signal, with a sinusoidal signal of an amplitude of 30 mm and a frequency of 0.2 Hz. The sinusoidal signals are input into the coordinated motion control system through the first node of the chain topology or the tree topology.

Fig. 6 and Fig. 7 are the tracking error curves of the 3 PMSLMs in the chain topology (the difference between the actual position signal of the motor and the reference signal) and the cooperative error curve (difference between the actual position signals of every two motors). It can be seen from Fig. 6 that the tracking error of the motor 1 is within ±0.3 mm, the tracking error of the motor 2 rises to about ±0.6 mm, while the tracking error of the motor 3 is expanded to within ±0.9 mm, that shows an increasing trend of the tracking error. The experimental phenomenon that the tracking error gradually becomes larger is caused by the structural characteristics of the chain communication topology itself. The one-way flow of the signal makes the error between the actual reference signal and the reference input signal of the 3 motors accumulate gradually. When there are more and more nodes in the system, it can be inferred that the error between the actual signal of the last node and the reference signal of the starting node will become larger and larger. From Fig. 7, it can be seen that in the chain communication topology, the cooperative precision of multiple motors can be controlled within ±0.6 mm.

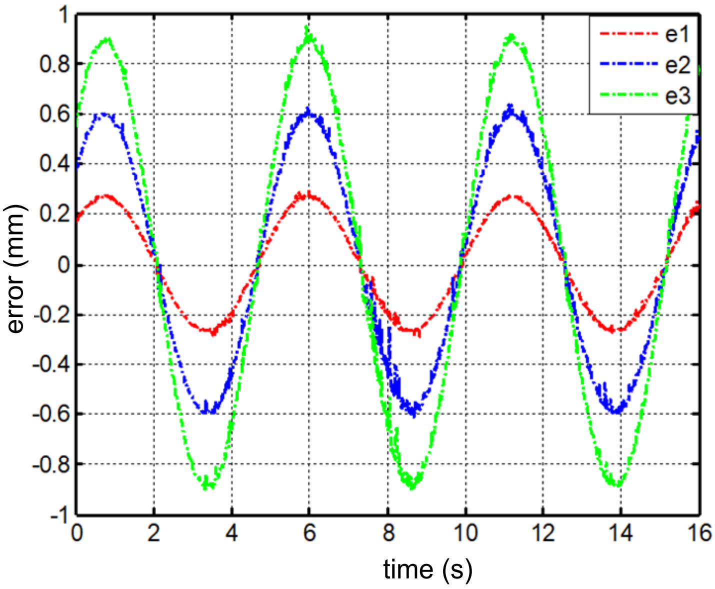


Fig. 6. PLMSM tracking error curve in chain structure

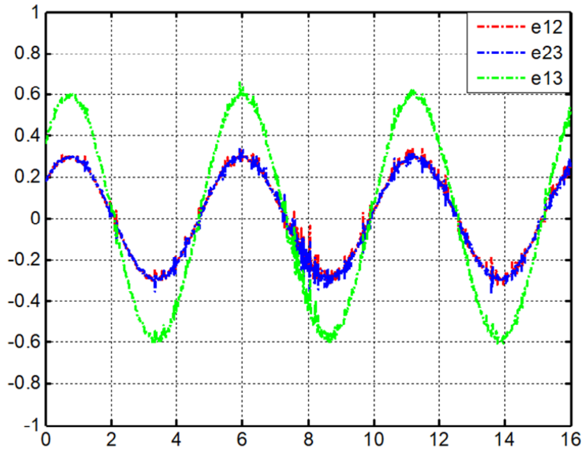


Fig. 7. Coordinated error curve of PMSLM in chain structure

Fig. 8 and Fig. 9 are the tracking error curves of 3 PMSLMs in a tree topology and the synergistic error curves between the motors. As can be seen from Fig. 9, the coordinated tracking of multiple motors can be controlled within ±0.3 mm. In the tree structure, both motor 2 and motor 3 receive information from motor 1, so that motor 2 and motor 3 are on the equal level in the system, which can be verified in Fig. 8 and Fig. 9, the tracking error curves of motor 2 and motor 3 are almost overlapping, reaching ±0.6 mm; the synergistic error curves between motor 1 and motor 2 and between motor 1 and motor 3 are almost overlapping, while the synergy error between motor 2 and motor 3 is almost zero.

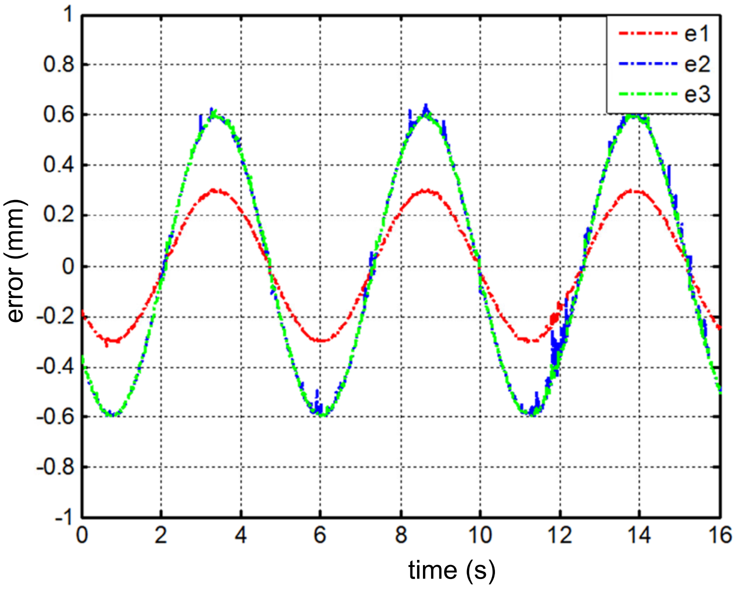


Fig. 8. PMSLM tracking error curve in tree structure

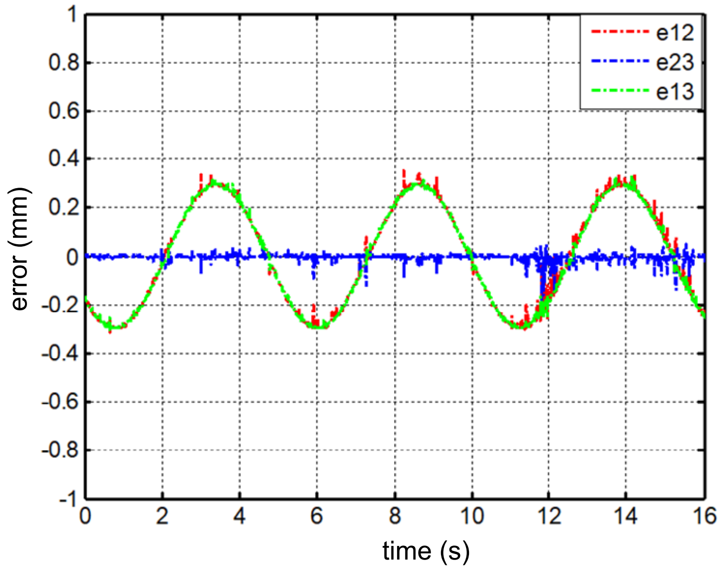


Fig. 9. Coordinated error curve of PMSLM in tree structure

In the tree topology and chain topology, the multiple-PMSLMs form a cooperative control system through the communication interfaces between them, each motor, however, the motor only refers to the motion state of itself and the one before it during operation, not taking the operating state of the adjacent motors (such as position, speed, etc.), so the overall cooperative performance of the entire system needs to be improved.

4.2 Experimental Study on Adjacent Deviation Coupling Cooperative Algorithm

In order to achieve better synergy accuracy, the author chooses the adjacent deviation coupling cooperative algorithm, which does not need to refer to the motion state of all the motors in the system, only need to refer to the state information of the two motors adjacent to itself. It reduces the calculation amount of the controller as well as retains certain state information for calculation. [14-17]. Fig. 10 is a block diagram showing the structure of a multi-linear motor cooperative control system using an adjacent deviation coupling cooperative algorithm.

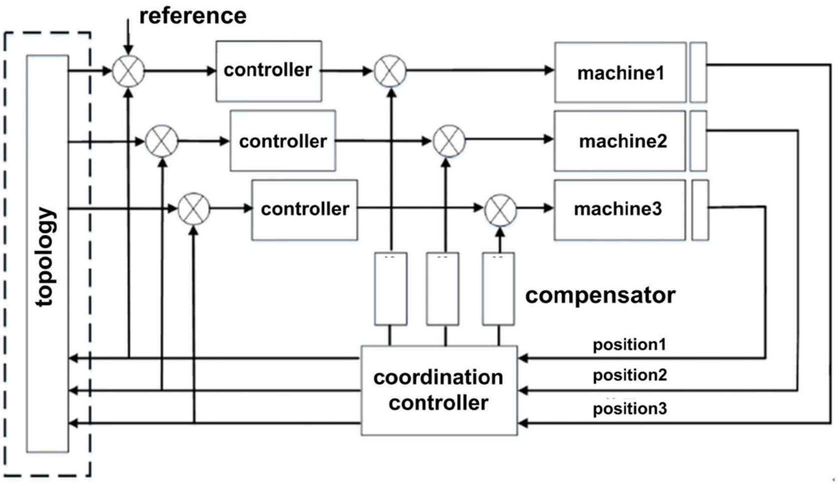
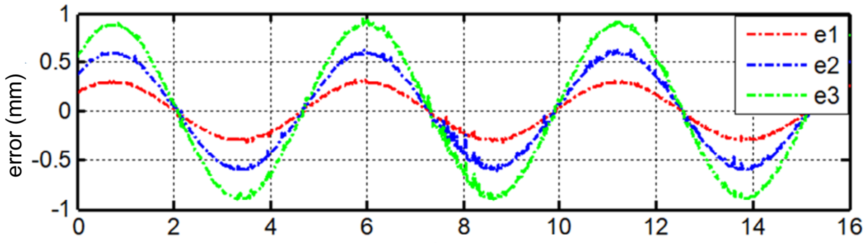


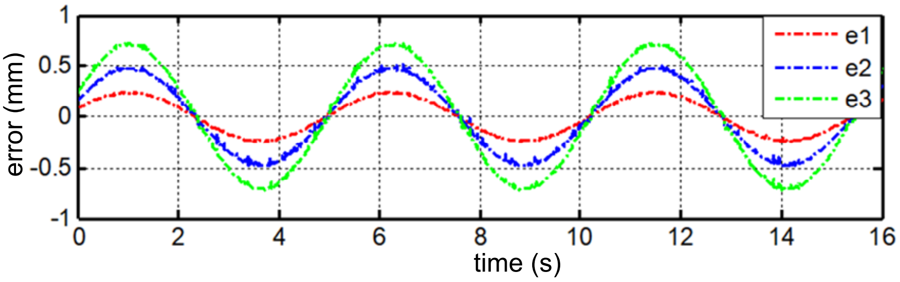
Fig. 10. Adjacent deviation coupling cooperative algorithm control block diagram

To verify the effectiveness of the proposed adjacent-coupling-coupling cooperative algorithm, the experiment of multi-linear motor cooperative motion control system is carried out again in chain topology and tree topology. The selected reference signal is still consistent with the previous section, a sinusoidal signal with an amplitude of 30 mm and a frequency of 0.2 Hz.

Based on the collaborative experiment carried out in the chain topology, Fig. 11 is a comparison of the tracking error before and after the application of the collaborative control algorithm; Fig. 12 is a comparison of the cooperative error before and after the application of the collaborative control algorithm. After the cooperative algorithm being applied, the tracking error of each motor in the chain topology is reduced, and the tracking error (that of the 3th motor) accumulated in the final node is reduced from 0.9 mm to 0.7 mm; The synergy precision between motors is also improved, and the errors between motor 1 and motor 2 and between motor 2 and motor 3 are reduced from 0.3 mm to 0.25 mm.

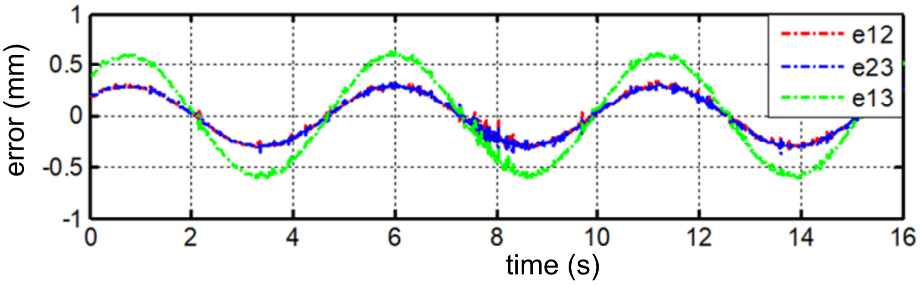


(a) Before the application



(b) After the application

Fig. 11. PMSLM tracking error before and after applying cooperative algorithm in chain topology



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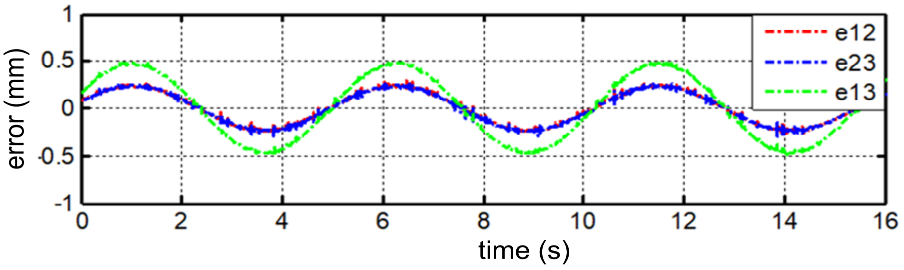
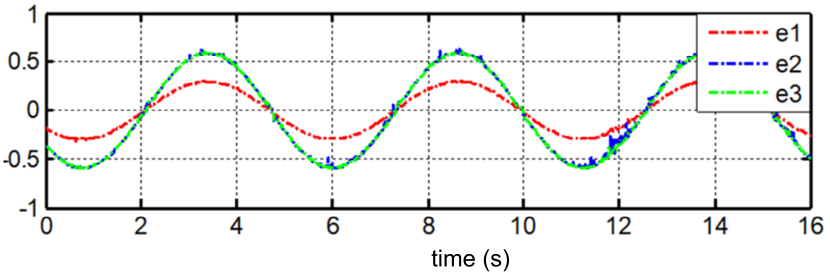


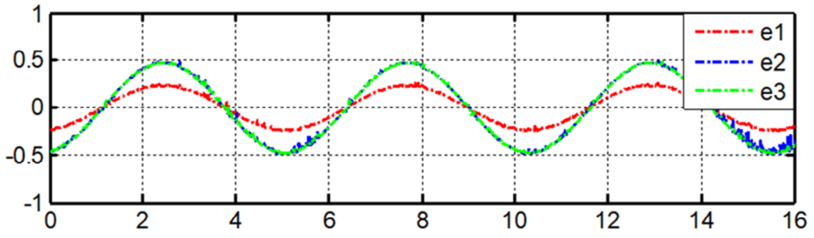
(b) After the application

Fig. 12. Coordinated error of PMSLM before and after applying cooperative algorithm in chain topology

The collaborative experiment based on the tree topology structure, Fig. 13 is the comparison of the tracking error before and after the application of the collaborative control algorithm; Fig. 14 is the comparison of the cooperative error before and after the application of the collaborative control algorithm. It can be seen from the figures that the tracking error curve and the cooperative error curve of the motor become smoother with the application the cooperative algorithm. The tracking errors of the 3 motors have been reduced. The maximum tracking error has been reduced from 0.6 mm to 0.5 mm, and the synergy error between motor 1 and motor 2 and between motor 1 and motor 3 have changed from 0.3mm to 0.25mm or so.

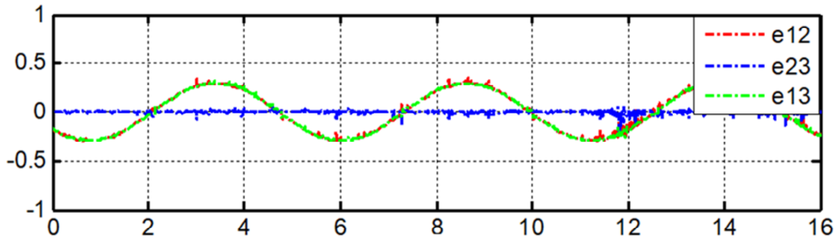


(a) Before the application

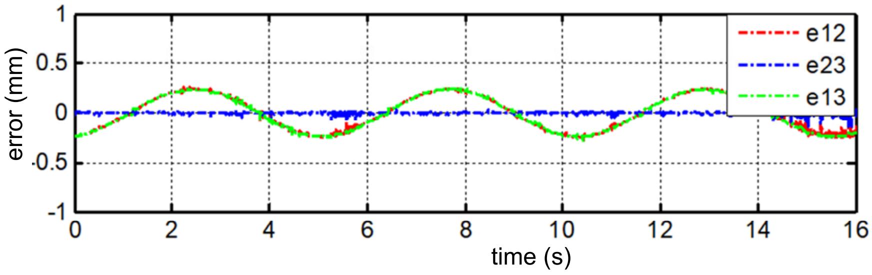


(b) After the application

Fig. 13. Comparison of PLMMS tracking error before and after applying cooperative algorithm in tree topology



(a) Before the application



(b) After the application

Fig. 14. PMSM cooperative error comparison diagram before and after using collaborative algorithm in tree topology

Combining the two cases above, after the application of the adjacent deviation coupling algorithm, the tracking accuracy of each motor and the synergy precision between multiple-motors are improved in both the chain structure and the tree structure. The tracking error of the motor and the reference signal can be reduced by 0.2 mm at most, and the coordination error between adjacent motors is reduced from 0.3 mm to 0.25 mm, with the synergy accuracy improved by about 17%.

5 Summary

In this essay, the collaborative control research of multi-PMSLM is carried out, and the experimental platform of the cooperative control system is built. The principle of fuzzy control and the cooperative control algorithm are applied to the collaborative control system to improve the tracking precision and coordination precision of the motion system. A cooperative motion platform of 3 PMSLMs is built on the simulation platform RT-LAB. At the same time, in order to improve the overall control effect of the multi-linear motor, a fuzzy PID controller is designed to improve the tracking accuracy of the single PMSLM. Compared with the conventional PID controller, the linear motor with fuzzy PID controller has higher tracking accuracy, which is about 25% higher. Research on the chain topology and tree topology based on multi- motors is carried out on the established multi-motor cooperative control platform. In the chain structure, the tracking error of the reference signal from the motor is gradually accumulated, and the tracking error of the most end node will reach the maximum; while in the tree topology, all the slave nodes except the master node are in the same position in the system, and the tracking error of them is almost the same.

The author proposes an adjacent deviation coupling cooperative algorithm and applies the algorithm to the constructed platform of the cooperative motion. The experimental results show that after the application of the adjacent deviation coupling algorithm, the tracking accuracy and coordination precision of the multiple-PMSLMs are improved. The tracking error of the motor and reference signal can be reduced by about 0.2 mm at most, and between adjacent motors. The synergy error between motors was reduced from the original 0.3 mm to 0.25 mm with the synergy accuracy increased by 17%.

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