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An Integration Enhanced Repetitive Path Planning Scheme for Omnidirectional Mobile Robot Manipulators

Qin Ding, Naimeng Cang, Yilin Yu, Qu Li, Dongsheng Guo

Abstract— **The repetitive path planning (RPP) is an important issue in the research of mobile robot manipulators. By utilizing the integration enhanced method, this paper proposes a new RPP scheme for omnidirectional robot manipulators. Differing from the existing RPP schemes, such an integration-enhanced RPP (IERPP) scheme can realize the RPP of omnidirectional mobile robot manipulators even in the presence of noise. Comparative simulation results under a specific omnidirectional mobile robot manipulator perturbed by constant and time-varying noises are presented to validate the effectiveness of the proposed IERPP scheme.**

Index Terms— **integration enhanced, repetitive path planning, omnidirectional mobile robot manipulators, noise, simulation.**

I. Introduction

In recent years, the mobile robot manipulator, composed of a mobile platform and a robot manipulator installed on the mobile platform, which is playing an increasingly important role in the fields of industry and science [1]–[6]. Due to flexibility, accuracy, and security, the mobile robot manipulator can conduct complex and/or repeated tasks more efficiently, thereby providing excellent support in many aspects. With regard to mobile robot manipulators, one of the fundamental issues is the repetitive path planning (RPP) [7]. It could be understood as that both the mobile platform and the robot manipulator installed on the platform need to simultaneously return to the start state after the end effector performs a pre planned path task. Especially, the non-repetitive motion may lead to the robot unpredictable behavior, and further generate disservice to mobile robot manipulators. Due to its importance, many researches related to RPP of mobile robot manipulators have gradually been made public [7]–[16].

The study of the non-repetitive problem first began with Klein and Huang [17], then Tchon relates the issue of repeatability to mobile robot manipulators , introducing repetitive motion directions for mobile robots [8]. In [9]–[11], Tchon and Jakubiak learned and researched more Jacobian pseudoinverse RPP schemes for the robot manipulators based on this research. Laying a more solid foundation for repeatability mechanism. After that, in [12], Xiao and Zhang discussed the RPP scheme based on quadratic programming (QP), In [13], Zhang *et al* also studied other QP-based RPP scheme for omnidirectional mobile robot manipulators. It is worth mentioning that the existing RPP schemes are assumed to no noise. Noise would have impacts on the effectiveness of a RPP scheme, and cause the scheme invalidation [18]–[20]. In this situation, the RPP purpose will not be realized. Therefore, it is worth designing and investigating an effective RPP scheme with the noise tolerance capability for mobile robot manipulators. Such a scheme can be robust to additive noise and make the mobile robot manipulator achieve repetitive motion simultaneously.

In this paper, based on the previous work [16], a new RPP programme is designed and studied for omnidirectional mobile robot manipulators by utilizing the integration enhanced method. Differing from the existing RPP schemes [7]–[15], such an integration-enhanced RPP (IERPP) scheme can achieve the RPP of mobile robot manipulators even in the presence of noise. And the reliability of the designed IERPP scheme was verified by comparing simulation results.

The content and structure of this research is divided into three parts. Section II deduces the formulation of the designed IERPP scheme. Section III provides the simulation results. Section IVsummarizes the conclusion. The main contributions of this article are as follows: follows.

(1) This paper designs a new IERPP scheme for omnidirectional mobile robot manipulators. Such a scheme, which can possess the suppression of additive noise, has not been reported in the current existing achievements.
(2) This paper bespeaks the simulation results with the consideration of constant noise and bounded time-varying noise, and confirms the effectiveness of the proposed IERPP programme. This paper is significant, as it provides new insights into the RPP scheme

II. New IERPP Scheme

In the section, the existing RPP programme based on Jacobian pseudoinverse is presented firstly. Then, by utilizing the integration enhanced method, the new IERPP scheme is designed for omnidirectional robot manipulators.

A. Preliminary

Universally, the motion of an omnidirectional mobile robot manipulator could be summarized as the following equations:

$$f(\vartheta(t)) = r_{\mathrm{d}}(t), \tag{1}$$

take $f(\cdot)$ as the non-linear operator, $r_{\mathrm{d}}(t) \in R^m$ as the expected motion of the end-effector route. And the status of the mobile platform $\vartheta(t) = [x_c(t); y_c(t); \phi(t); \theta(t)] \in R^{3+n}$

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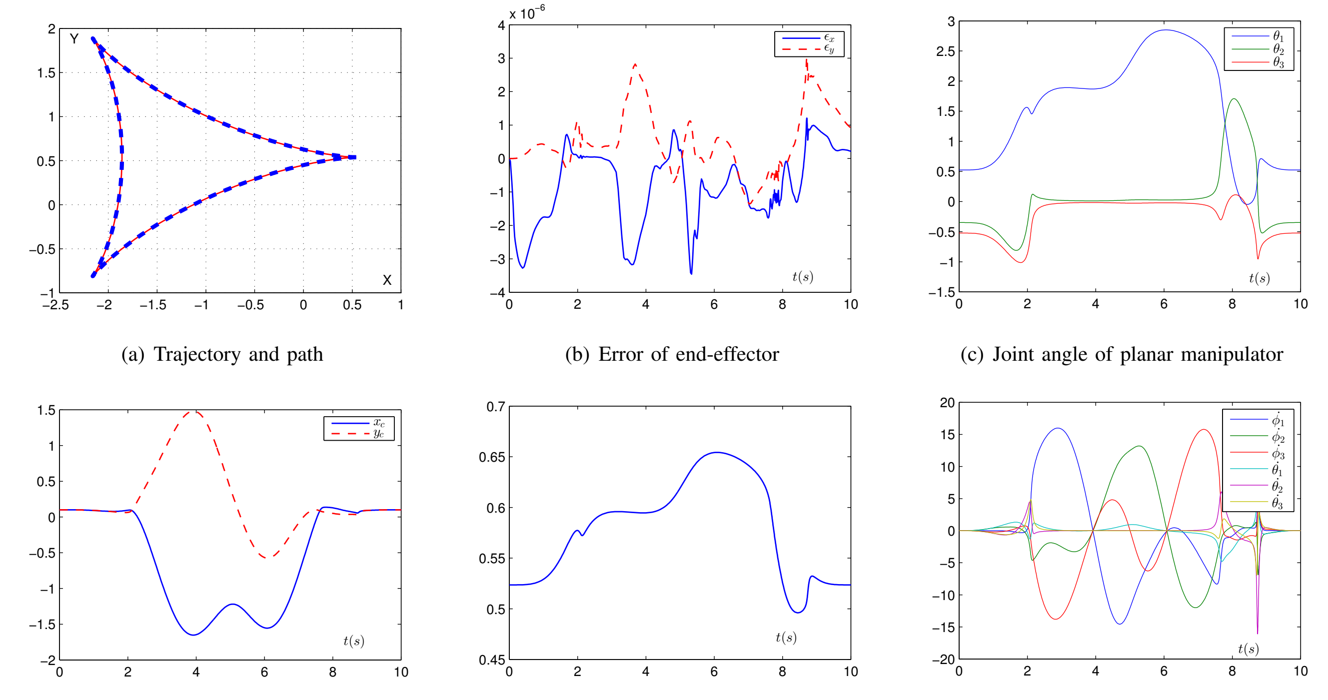


(a) Trajectory and path

(b) Error of end-effector

(c) Joint angle of planar manipulator

(d) Position of platform

(e) Platform heading angle

(f) Combined velocity of mobile robot

Fig. 1. Using the RPP scheme (6) to track the tricuspid path with zero noise considered.

TABLE I

JOINT ERROR BETWEEN THE END AND START STATUSES OF THE OMNIDIRECTIONAL MOBILE ROBOT MANIPULATOR USING THE RPP PROGRAMME (6), CONSIDERING ZERO NOISE.

#	end status $\theta(10)$	error $\lvert\theta(10)$-$\theta_0\rvert$
x_c	0.100000269581501	$2.695815013442626\times10^{-7}$
y_c	0.100000247221292	$2.472212918686045\times10^{-7}$
ϕ	0.523598836299145	$6.070084590525937\times10^{-7}$
θ_1	0.523597347832531	$0.142776576750325\times10^{-5}$
θ_2	-0.349062476223800	$0.337417506596216\times10^{-5}$
θ_3	-0.523595879050928	$0.289654737117839\times10^{-5}$

and the location of the platform baseplate $x_p(t)$ and $y_p(t)$ indicating the mark X and Y, and the central point C, $\theta(t) \in R^n$ as the joint angle, and $\phi(t) \in R$ as the heading angle. Given a closed path r_d in (1), the RPP of the omnidirectional mobile robot manipulator is realized when and only when x_c, y_c, ϕ, and θ regain the initial states x_{c0}, y_{c0}, ϕ_0, and θ_0. That is, after completing the path tracking task, $\vartheta \to \vartheta_0$. Owing to nonlinearity, it is generally not easy to immediately solve though formula (1) to determine the repeated solution.

The relationship generated by the differentiation of (1) relative to time t is as follows:

$$H(\vartheta)\dot{\vartheta} = \dot{r}_\text{d}, \tag{2}$$

In this speed level relationship $H(\vartheta) = \partial f/\partial\vartheta \in R^{m\times(3+n)}$. r_d obtained $\dot{r}_\text{d}$ by calculating the time. then $\dot{\vartheta} = [\dot{x}_c; \dot{y}_c; \dot{\phi}; \dot{\theta}]$, wherein x_c, y_c, and ϕ are also obtained $\dot{x}_c$, $\dot{y}_c$, and $\dot{\phi}$ by calculating the time, then with $\dot{\theta}$ as the joint velocity of the mobile robot manipulator. In addition, the kinematic relationship for the mobile platform is presented:

$$\begin{bmatrix}\dot{x}_c\\ \dot{y}_c\\ \dot{\phi}\end{bmatrix} = A\dot{\varphi} = A\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\end{bmatrix}, \tag{3}$$

the speed of the wheels is $\dot{\varphi} \in R^3$, and the expression for $A \in R^{3\times3}$ is as follows:

$$A = \begin{bmatrix}-\frac{2}{3}r\sin(\phi) & -\frac{2}{3}r\sin(\frac{\pi}{3}-\phi) & \frac{2}{3}r\sin(\frac{\pi}{3}+\phi)\\ \frac{2}{3}r\cos(\phi) & -\frac{2}{3}r\cos(\frac{\pi}{3}-\phi) & -\frac{2}{3}r\cos(\frac{\pi}{3}+\phi)\\ \frac{r}{3d} & \frac{r}{3d} & \frac{r}{3d}\end{bmatrix},$$

where $r \in R$ is the radius of the mobile platform wheel, and $d \in R$ is the distance from C to the contact point of the wheel and the ground. Then the overall Kinematics equation can be further expressed:

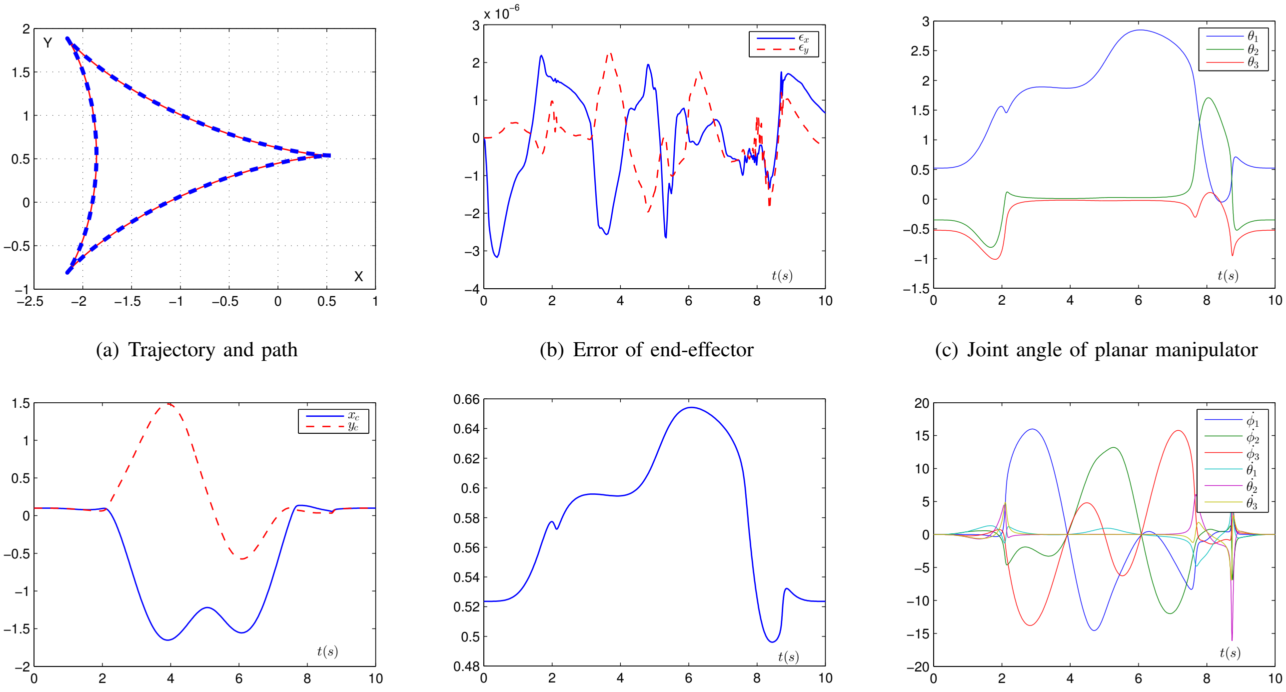
$$H(\vartheta)\dot{\vartheta} = H(\vartheta)\begin{bmatrix}A & 0\\ 0 & I_n\end{bmatrix}\dot{q} = J\dot{q} = \dot{r}_\text{d}, \tag{4}$$

Among them, $\dot{q} = [\dot{\varphi}; \dot{\theta}] \in R^{3+n}$ represents a further combined velocity vector, then the identity matrix $I_n \in R^{n\times n}$. At this stage, the initial path planning of the mobile robot can be determined as finding $\dot{q}$ in (4) through the given $\dot{r}_\text{d}$.

The general formulation of the pseudoinverse-type path planning project is presented as below:

$$\dot{q} = J^\dagger\dot{r}_\text{d} + (I_{3+n} - J^\dagger J)v, \tag{5}$$

in the above formula $J^\dagger \in R^{(3+n)\times m}$ as the pseudoinverse of



(a) Trajectory and path

(b) Error of end-effector

(c) Joint angle of planar manipulator

(d) Position of platform

(e) Platfoem heading angle

(f) Combined velocity of mobile robot

Fig. 2. Using the IERPP scheme (8) to track the tricuspid path with zero noise considered.

TABLE II
JOINT ERROR BETWEEN THE END AND START STATUSES OF THE OMNIDIRECTIONAL MOBILE ROBOT MANIPULATOR USING THE IERPP PROGRAMME (8), CONSIDERING ZERO NOISE.

#	end status $\theta(10)$	error $\lvert\theta(10) - \theta_0\rvert$
x_c	0.100000126917914	$1.269179141782928\times10^{-7}$
y_c	0.100000100139373	$1.001393725580391\times10^{-7}$
ϕ	0.523598821047252	$4.544895304547936\times10^{-8}$
θ_1	0.523597058328547	$0.171726975173314\times10^{-5}$
θ_2	-0.349064855035296	$0.099536356995555\times10^{-5}$
θ_3	-0.523597614555475	$0.116104282332774\times10^{-5}$

J, and the identity matrix $I_{3+n} \in R^{(3+n)\times(3+n)}$, in addition, there are optimization vectors that can be adjusted $v \in R^{3+n}$. The design of a specific v results in the corresponding route planning programme for mobile robot manipulators. Specifically, to reach the RPP of omnidirectional mobile robot manipulators, the programme designed in [16] is given by

$$\dot{q} = J^{\dagger}(\dot{r}_{\mathrm{d}} - \gamma(f(\vartheta) - r_{\mathrm{d}})) + k(I_{3+n} - J^{\dagger}J)Mp, \quad (6)$$

with $\gamma > 0 \in R$, $k > 0 \in R$, besides, in the formula $M \in R^{(3+n)\times(3+n)}$ and another defined setting is$p \in R^{(3+n)}$ as follows:

$$M = \begin{bmatrix} A^{-1} & 0 \\ 0 & I_n \end{bmatrix} \text{ and } p = \begin{bmatrix} p_{xy0} - p_{xy} \\ \cos(\phi)(\sin(\phi_0) - \sin(\phi)) \\ \theta_0 - \theta \end{bmatrix},$$

In the formula $p_{xy0} = [x_{c0}; y_{c0}]$ then another state $p_{xy} = [x_c; y_c]$. It is worth noting that the RPP scheme (6) evolved from (5) by incorporating retroaction and projecting $v = kMp$.

Lemma 1: *Given that no singularity occurs in path planning, the presented scheme (6) comprises the RPP property for omnidirectional mobile robot manipulators.*

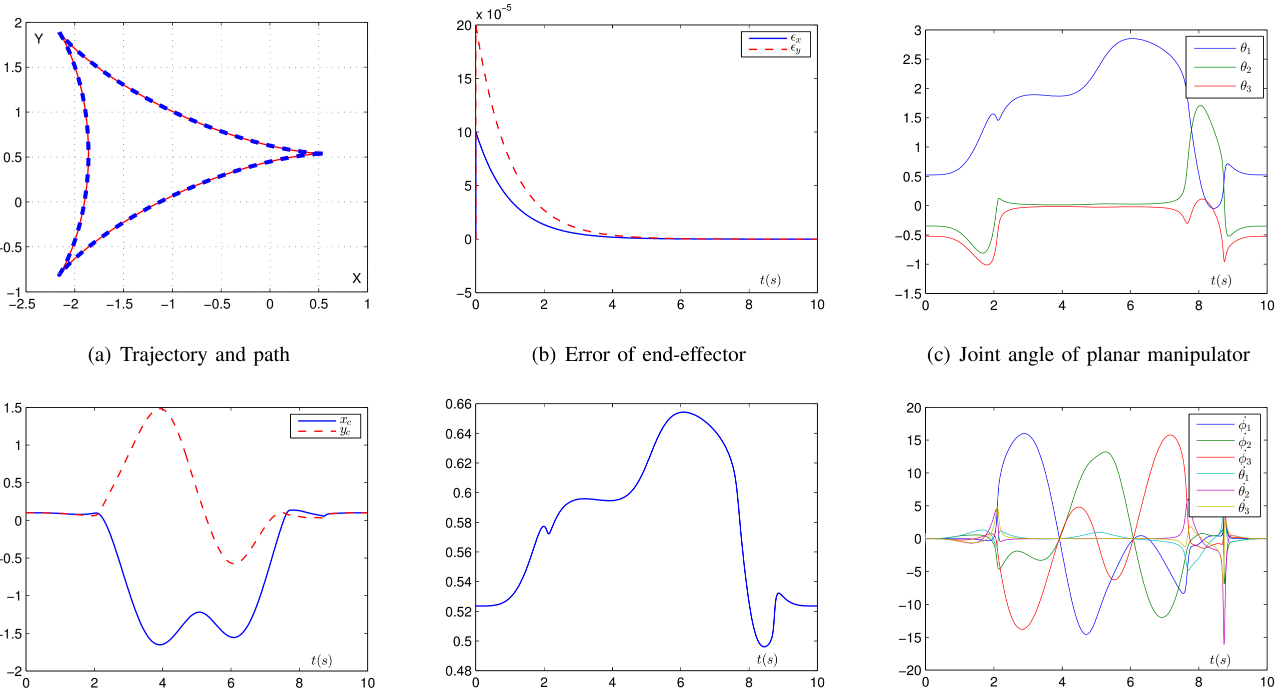
B. Scheme Formulation

In this subsection, we discuss scheme (6) about noise, where θ_0 is the initial state of the joint, and it contains an adjustable parameter $k > 0$. This scheme (6) has been proven to be effective in existing research. However, when there are noise factors in the environment, Scheme (6) may generate divergent tracking errors, leading to deviation or even failure of the mobile robot operator

Therefore, we put forward the IERPP solution for the noise of the operating environment. If there is noise, the equation becomes the following formulation:

$$H(\theta)\dot{\theta} = \dot{r}_{\mathrm{d}} + \delta, \quad (7)$$

where $\delta \in R^m$ represents the increased noise, which in this scheme includes the differential error and implementation error of r_{d}. Adding noise in the environment δ, (7) cannot accurately track repetitive motion paths as in a zero noise environment. So that the accuracy and reliability of the previous scheme (6) are reduced and could not effectively complete the task. In order to counteract the interference of noise and ensure that robots can still efficiently complete tasks, a new approach is proposed that includes the information, which is the proportional and integral of r_{d}.



(a) Trajectory and path

(b) Error of end-effector

(c) Joint angle of planar manipulator

(d) Position of platform

(e) Platform heading angle

(f) Combined velocity of mobile robot

Fig. 3. Using the IERPP scheme (8) to track the tricuspid path with constant noise considered.

TABLE III

JOINT ERROR BETWEEN THE END AND START STATUSES OF THE OMNIDIRECTIONAL MOBILE ROBOT MANIPULATOR USING THE IERPP PROGRAMME (8) THAT CONSIDERS CONSTANT NOISE.

#	final state $\theta(10)$	error $\lvert\theta(10)-\theta_0\rvert$
x_c	0.100000005897433	$5.897433277834985\times10^{-8}$
y_c	0.100000003320618	$3.320618419122567\times10^{-8}$
ϕ	0.523598901293225	$1.256949260231011\times10^{-7}$
θ_1	0.523598648179843	$0.127418455897477\times10^{-6}$
θ_2	-0.349065843406733	$0.006992132539629\times10^{-6}$
θ_3	-0.523598734976584	$0.040621715213796\times10^{-6}$

$$\begin{aligned}\dot{q} =&J^{\dagger}(\dot{r}_{\mathrm{d}} - \alpha(f(\vartheta) - r_{\mathrm{d}}) - \beta\int(f(\vartheta) - r_{\mathrm{d}})dt + \delta)\\ &+ k(I_{3+n} - J^{\dagger}J)Mp,\end{aligned} \tag{8}$$

Include the designed Variables $\alpha > 0$ and $\beta > 0$ in the formula, and their relationship satisfies $\alpha^2 > 4\beta$. And among these parameters, k has characteristics related to RPP of (8), while α and β are related to the ability to suppress noise. In the new scheme, noise is suppressed by adjusting the reasonable values of k, α, and β, and it can simultaneously complete the repetitive route planning and control of the mobile robotic arm manipulator.

The proposed new IERPP scheme (8) adds variables related to the derivative, proportional, and integral information of r_d. These changes enable (8) to have proportional-integral-derivative properties regarding r_d. It improves the ability to tolerate noise in the proposed new scheme (8), changes scheme (6) to produce non divergent errors instead of divergent errors when there is noise interference in the environment. In addition, some theoretical results of the IERPP scheme (8) are as follows:

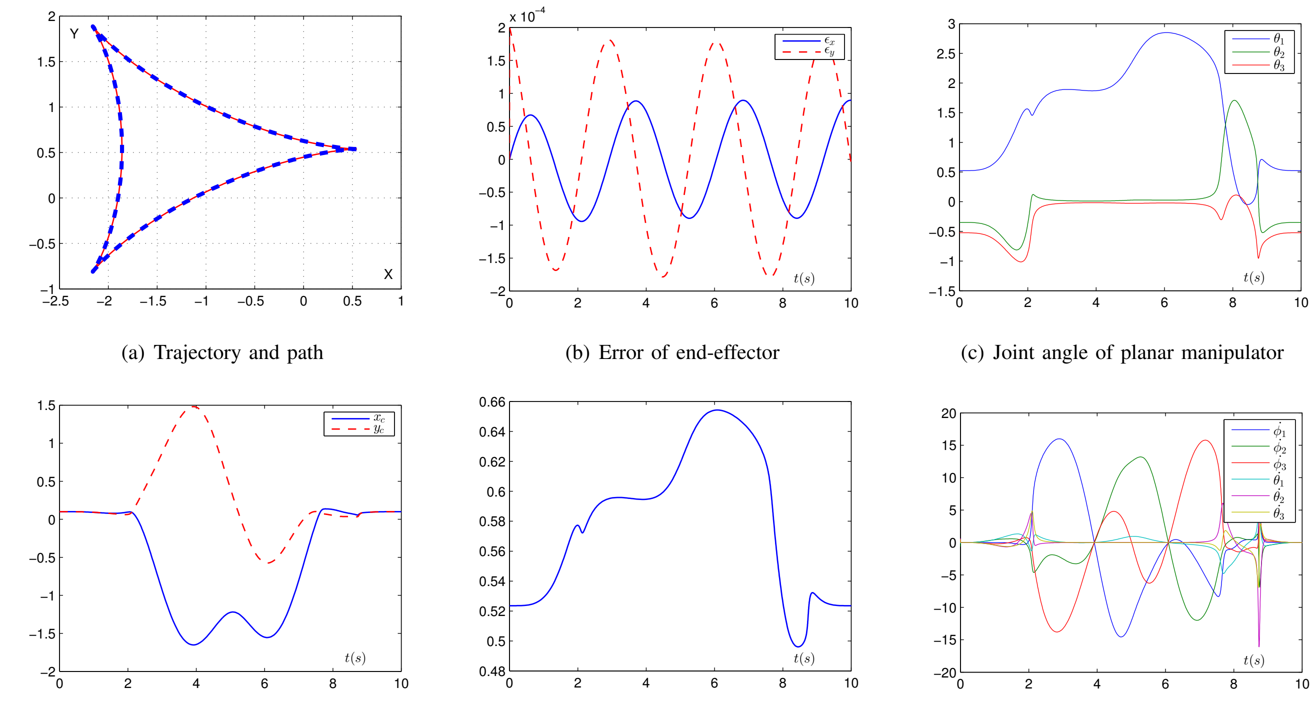
Lemma 2. *If the noise is ignored (i.e., $\delta = 0$), the trajectory of the proposed new RPP scheme (8) with error $\epsilon(t) = f(\theta) - r_d \in R^m$ tends to be stable.*

Lemma 3. *If noise is considered, the tracking error $\epsilon(t)$ of the designed new IERPP programme (8) stick to the below theorem.*

(1) *If the constant noise pertains (i.e., $\delta = c \in R^m$), the track of $\epsilon(t)$ exhibits convergence, and there is no error during steady state..*

(2) *If the bounded time-varying noise δ pertains, the track of $\epsilon(t)$ exhibits boundedness, and When using sufficiently large α and β, the steady-state error will have an arbitrarily small upper limit.*

These two lemmas can be derived from [21]–[23], Therefore, the new IERPP scheme has reliable theoretical support. Theoretically, omnidirectional mobile robots can keep the tracking error of the end effector within a small range under the new scheme. Additionally, by choosing the values of α and β reasonably, the value of E can be controlled within a small range. Overall, with the above theoretical support, the new IERPP scheme (8) proposed in this study can demonstrate better performance for omnidirectional mobile robots.



(a) Trajectory and path

(b) Error of end-effector

(c) Joint angle of planar manipulator

(d) Position of platform

(e) Platform heading angle

(f) Combined velocity of mobile robot

Fig. 4. Using the IERPP scheme (8) to track the tricuspid path with bounded time-varying noise noise considered.

III. Actual Verification and Comparison

In this section, simulation and comparison of the new scheme were conducted to verify that the designed IERPP programme(8) is more effective compared to the original RPP scheme. In the simulation, the omnidirectional mobile robot selects a three wheel platform and a three link robotic arm.

In these examples, two schemes were simulated for the mobile robot manipulator, at this point, set the initial state $\theta_0 = [p_{xy0}; \phi_0; \theta_0] = [0.1; 0.1; \pi/6; \pi/6; -\pi/9; -\pi/9]$, in addition, the radius is 0.6 m, in this discuss, the desired path of the end-effector is set as the tricuspid path. Based on this, the simulation and comparison results of the two schemes under different noises are obtained to prove that the new IERPP scheme (8) can perform repeated path planning more correctly and effectively than the previous scheme (6) when there is noise in the environment.

A. Zero Noise Situation

First, under zero noise conditions, simulation and comparison are conducted between the previous RPP scheme (6) and the new IERPP scheme (8), and the corresponding simulation data of the two schemes are presented in Figs. 1 and 2 and Tables I and II.

Fig. 1 and Table I are simulation images and data obtained using the RPP scheme with $\alpha = 1$. The error between the initial and final states of the end-effector after completing the task is $\epsilon = f(\theta) - r_d \in R^2$. It can be seen from 1(a) that the motion track of the mobile robot manipulator conforms to the tricuspid route. But if the interference of noise is considered,

TABLE IV

Joint error between the end and start statuses of the omnidirectional mobile robot manipulator using the IERPP programme (8) with bounded time-varying noise considered.

#	end status $\theta(10)$	error $\lvert\theta(10) - \theta_0\rvert$
x_c	0.100022337457090	$2.233745709011303\times10^{-5}$
y_c	0.100018634505951	$1.863450595095129\times10^{-5}$
ϕ	0.523587047007927	$1.172859037201768\times10^{-5}$
θ_1	0.523361665708030	$0.237109890268816\times10^{-3}$
θ_2	-0.348851953260494	$0.213897138372332\times10^{-3}$
θ_3	-0.523381758706898	$0.217016891400856\times10^{-3}$

the scheme (6) will come up against the divergence problem of error $\epsilon(t)$. Fig. 2 and Table II show the data of the IERPP scheme using $\alpha = 1$ and $\beta = 1$. In the images of Fig. 2(a) and Fig. 2(b), after completing the route tracking task according to (8), the tracking error of the end-effector is less than 3×10^{-5} m.

By contrast, the proposed scheme (8) can still stabilize in a reasonable error, in addition, (8) has better tracking accuracy for mobile robot manipulators than (6).

B. Constant Noise Situation

Second, increasing the interference of constant noise in the environment to investigate scheme (8), and the constant noise in it is $\delta(t) = c = [0.1; 0.2]$. Fig. 3 and Table III are the simulation results obtained by Scheme (8) after using $\alpha = 1000$ and $\beta = 1000$. Compared with the previous RPP scheme, the new IERPP scheme can show smaller errors under the constant noise, Tab. III shows that the end-effector planning error is decreased to a small value which is in the order 10^{-9} m.

Accordingly, The above simulation data confirm that the designed IERPP scheme (8) can effectively complete repetitive path planning for the redundant Mobile Robot if there is constant noise in the environment

C. Bounded Time-varying Noise Situation

Third, under the same comparison programme, simulations were conducted on the scheme with bounded time-varying noise. The noise was set to $\delta(t) = [0.1\sin(2t); 0.2\cos(2t)]$, and $\alpha = 1000$, $\beta = 1000$ in the scheme (8). The corresponding experimental data can be seen in Fig. 4 and Table IV. In Fig. 4(a), we can clearly see that the robot end-effector successfully tracked the route of tricuspid path under the condition of bounded time-varying noise interference. Fig. 4(b) represents the tracking error of the robot, and it can be observed that the tracking error is a bounded value with a maximum value of 10^{-4} m. Then, the error between the start and end statuses of the mobile robot manipulator end-effector after completing the corresponding path using Scheme (8) is shown in Table IV, these data confirm that the proposed scheme (8) successfully completed the planning of repeated path, Based on the above simulation data, it can be concluded that despite the presence of time-varying noise interference, Scheme (8) can still enable the omnidirectional mobile robot manipulator to complete repeated route planning.

In conclusion, the above simulation data (i.e., Figs. 1–4 and Tables I–IV) indicate that the designed IERPP programme (8) can be successfully and effectively executed in the repeated route planning of omnidirectional mobile robots with time-varying noise.

IV. Conclusion

In this document, we propose a new IERPP programme for omnidirectional mobile robot manipulators by utilizing the integration enhanced method. The feasibility of the designed programme has been confirmed through theoretical analysis and simulation experiments, which can achieve RPP for omnidirectional mobile robots. The simulation and comparison results of different instances under constant noise and bounded time-varying noise interference were simulated to demonstrate the superiority of the new IERPP programme (8) compared to the previous RPP scheme (6).

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