Proceedings of the 4th International Conference on Software Engineering and Machine Learning
DOI: 10.54254/2755-2721/2026.32226

Compliant Control for Primer Pre-Tightening in Assembly Processes

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Abstract. To address the issue of thread damage caused by alignment deviation during the assembly of primers and cartridge threads in small arms munitions, a compliant pre-tightening method based on position impedance control is proposed. Firstly, the characteristics of primer and cartridge assembly, similar to bolt and nut assembly, are analyzed, clarifying that the pre-tightening stage requires both preliminary thread fitting and contact force control. Secondly, a position-based impedance control model is established, mapping the contact force deviation to end-effector pose corrections through the impedance controller, achieving force and position hybrid regulation. Furthermore, through simulation, the effects of impedance parameters such as inertia, damping, and stiffness on the dynamic response of contact force are analyzed to select an appropriate parameter combination. Finally, simulation verification is carried out under a 5° initial axial angle error. The results show that this method can correct the angular deviation to nearly zero within 2 seconds while stabilizing the contact force around 6 N, effectively preventing thread damage. This provides a reference for the robotic automation of precise threaded assembly in munitions.

Keywords: compliant control, impedance control, threaded assembly, pre-tightening

1. Introduction

As a new type of ammunition, the primer of the surface-source jamming bomb and the assembly quality of the cartridge case are directly related to the reliability of the fuze function and the safety of use [1]. The assembly structure is similar to a bolt-and-nut connection, and this process largely relies on manual operations, which results in low efficiency, poor consistency, and easy damage to the threads, necessitating the introduction of robotic automated assembly technology [2]. The key task of robotic thread assembly is the accurate alignment of the thread start section and compliant control of the contact force [3]. During the pre-tightening stage, there may still be slight axial misalignment or positional deviation between the primer and the threaded port. If pure position control is used to force the thread in, it may cause thread jamming. Therefore, it is necessary to ensure initial thread engagement while keeping the contact force within a reasonable range. This paper focuses on the pre-tightening of primers for surface-source jamming bombs, employing a position-based impedance control method [4]. Through simulation, it analyzes the effect of impedance parameters on system response and validates the effectiveness of this method for force

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tracking and pose correction under conditions of initial angular deviation, providing a technical reference for automated ammunition assembly.

2. Principle of position-based impedance control

As shown in Figure 1, this is a schematic diagram of position-based impedance control, composed of a force control loop and a position control loop [5]. The control concept is to convert the deviation between the actual contact force fed back from the outer loop and the desired force into a position correction e through the impedance controller $1/\left(Ms^2+Bs+K\right)$, and superimpose it onto the desired trajectory X_d to generate a new execution trajectory X_r . This trajectory serves as the input to the position control inner loop, achieving coordinated control of the robot end-effector's force and position, thereby realizing the desired force tracking effect.

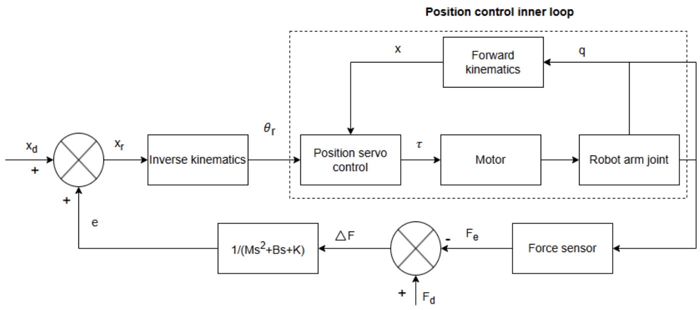

Figure 1. Position-based impedance control diagram

The basic principle of a position-based impedance controller can be expressed as:

$$\Delta F=M\ddot{E}+B\dot{E}+KE \tag{1}$$

In the formula, M, B, and K are the inertia, damping, and stiffness coefficients of the impedance parameters, respectively; E is the trajectory correction amount, and ΔF is the deviation of the actual contact force F_e from the desired contact force F_d .

The basic principle of the position-based impedance controller, after applying the Laplace transform, yields the transfer function between the trajectory correction and the force deviation:

$$\frac{E(s)}{\Delta F(s)}=\frac{1}{Ms^2+Bs+K} \tag{2}$$

The relationship between the executed trajectory X_r and the desired trajectory X_d is:

$$X_r=X_d+E=X_d+\Delta F\cdot\frac{1}{Ms^2+Bs+K} \tag{3}$$

The contact between the robot and the environment can establish a stiffness model:

$$F_e=K_e(X_r-X_e) \tag{4}$$

In the formula, K_e is the stiffness coefficient of the environment, X_r is the executed trajectory, and X_e is the position of the environment. By substituting these into the formula for the actual contact force and the desired contact force, the force error can be obtained:

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$$\Delta f = f_d - f_e = f_d - K_e(x_r - x_e) \tag{5}$$

According to the trajectory correction formula, the dynamic relationship of the force tracking system is obtained:

$$\Delta f(Ms^2 + Bs + K + K_e) = (Ms^2 + Bs + K)[f_d - K_e(x_d - x_e)] \tag{6}$$

From this, the steady-state force tracking error can be derived:

$$\Delta f_{ss} = \frac{KK_e}{K+K_e}\left(\frac{f_d}{K_e} - x_d + x_e\right) \tag{7}$$

It can be seen that the steady-state force tracking error Δf_{ss} depends on the environmental stiffness K_e and the environmental position x_e . If you want the steady-state force tracking error to be 0, the desired trajectory needs to be met:

$$x_d = x_e + \frac{f_d}{K_e} \tag{8}$$

3. Impedance parameter simulation analysis

3.1. Simulation model construction

The impedance controller has three parameters: inertia parameter M, damping parameter B, and stiffness parameter K. By adjusting these three parameters, the robot's end effector can exhibit different compliance characteristics. Therefore, selecting appropriate impedance control parameters is related to the robot's assembly accuracy and whether it can meet the requirements of the pre-tightening task. This section will discuss the effects of impedance parameters through simulation.

Based on the principle of position-based impedance control, simulation is carried out using Matlab. Figure 2 shows the simulation model, where the robot system is a two-link dynamic model. The robot position control algorithm is based on PD control, and the control variable method is used to regulate changes in impedance parameters to analyze their impact. The simulation parameters are set as follows: desired contact force F_d = 6 N, environment stiffness K_e = 800 N/m, environment position x_e = 0 m, desired trajectory x_d with zero force tracking error at 0.0075 m, simulation duration of 2 s, time step of 0.001 s, and solved using the fourth-order Runge-Kutta method.

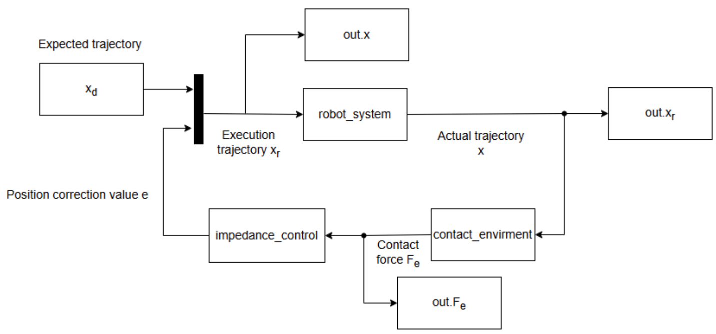

Figure 2. Location-based impedance control simulation model diagram

DOI: 10.54254/2755-2721/2026.32226

3.2. Analysis of the influence of inertia parameter M

First, we respectively take the inertia parameter M as 1, 2, 4, and 8, with the fixed parameters B = 30 and K = 300, and perform simulations to obtain the actual contact force Fe variation curve between the robot and the environment, as shown in Figure 3.

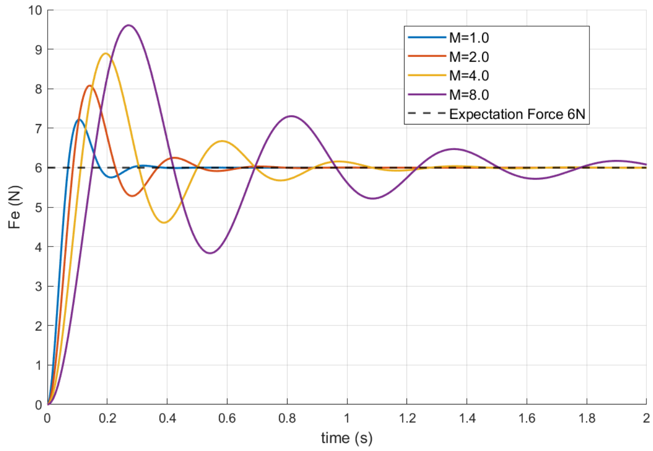

Figure 3. The effect of the inertial parameter M on contact force

From the figure, it can be seen that the inertia parameter M has little effect on the system's steady-state error, and the final contact force will stabilize at around 6 N. However, when the value of M is small, the system has less overshoot and can stabilize faster. As M gradually increases, the amount of overshoot and the settling time of the system also increase, indicating that the value of M affects the system's overshoot and adjustment time. Therefore, in practical applications, to improve the system's dynamic response performance during the contact process, M should be chosen to be smaller. In the robot assembly process, M can be equivalent to the inertia mass of the assembly shaft. The smaller the mass of the shaft, the smaller the inertia, the faster the robot responds, and the quicker the system stabilizes.

3.3. Analysis of the influence of inertia parameter B

Set the damping parameter B to 10, 40, 80, and 150 respectively, while keeping M=3 and K=300 unchanged. Simulations were performed to obtain the simulation curves of the contact force Fe, as shown in Figure 4. From the figure, it can be seen that under different values of B, the system contact force can still stabilize at 6 N, indicating that the damping parameter B has little effect on the system's steady-state error. However, when B is small, the system exhibits greater overshoot and longer settling time. As the value of B increases, the system overshoot is significantly reduced, and the response speed becomes faster. When B gradually increases to a certain point, the system no longer exhibits overshoot, but the response time increases, indicating that the value of B affects both the system overshoot and response speed. Therefore, when choosing the value of the damping parameter B, it should be selected as large as possible without increasing the response time, so as to suppress overshoot and improve the system response speed.

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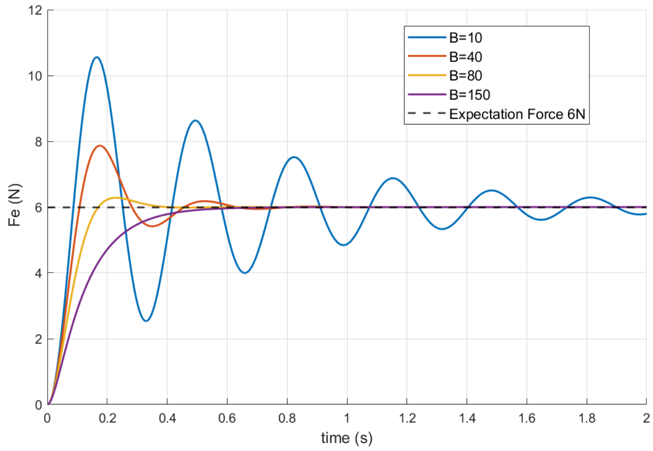

Figure 4. The effect of the inertial parameter B on contact force

3.4. Analysis of the influence of inertia parameter K

Similarly, the stiffness parameter K is taken as 10, 200, 400, and 800, with M=3 and B=30, for simulation to obtain the variation curve of the contact force Fe, as shown in Figure 5.

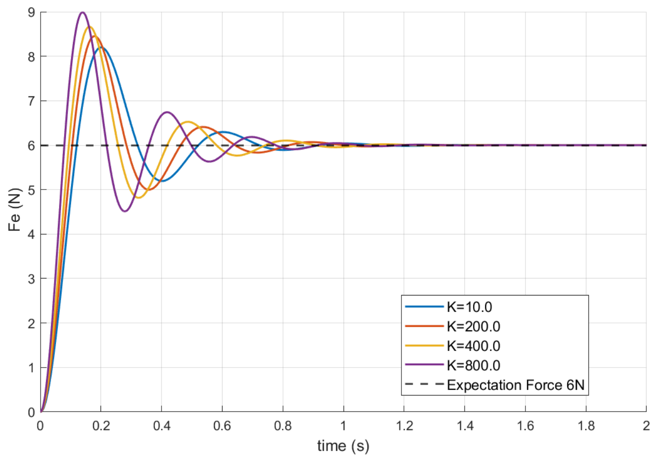

Figure 5. The effect of the inertial parameter K on contact force

The analysis results indicate that different stiffness parameters can all stabilize the system contact force at 6 N, suggesting that K has little effect on the steady-state error. However, the larger the K value, the faster the system response, but the greater the overshoot, indicating that the stiffness parameter K affects the system's overshoot and response speed, which is opposite to the effect of the damping parameter B. Therefore, under the condition that the system does not exhibit overshoot, the stiffness parameter K should be taken as large as possible to improve response speed.

4. Pre-tightening process simulation verification

To simulate the actual assembly error of a robot pre-tightening the primer on the cartridge case, the angular deviation between the primer and the central axis of the cartridge case thread is set to 5 degrees. Based on the simulation analysis of impedance parameters, the parameters of the position-based impedance control algorithm are set as: M=0.5, B=30, K=0.5, desired contact force F_d =6N.

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The force change during the pre-tightening process in the simulation experiment is shown in Figure 6. The contact force slightly increases at the initial moment of contact, and then quickly stabilizes around 6 N, indicating that the position-based impedance control algorithm can effectively regulate force output, making the pre-tightening process safe and reliable.

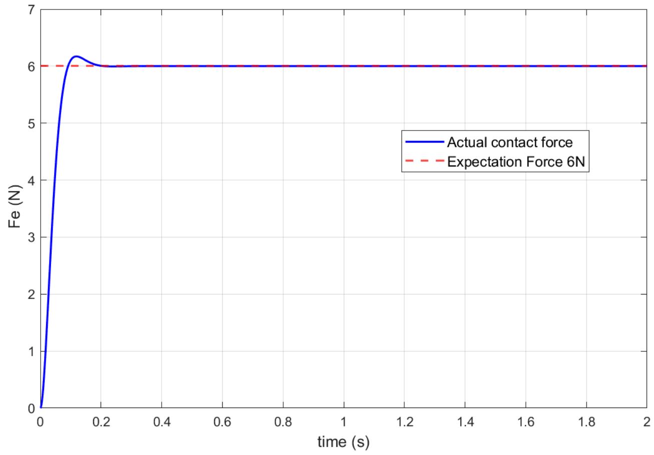

Figure 6. Force variation diagram of the pre-tightening process

In the simulation experiment, the variation of the primer and the cartridge center misalignment angle is shown in Figure 7. The initial misalignment angle was 5 degrees, and under position-based impedance control, it showed a rapid decay trend. The misalignment angle quickly converged close to 0, indicating that the robot end-effector can quickly correct the slight alignment errors between the primer and the cartridge thread. The misalignment curve is smooth, with no significant oscillations, indicating that the impedance parameters can ensure system stability.

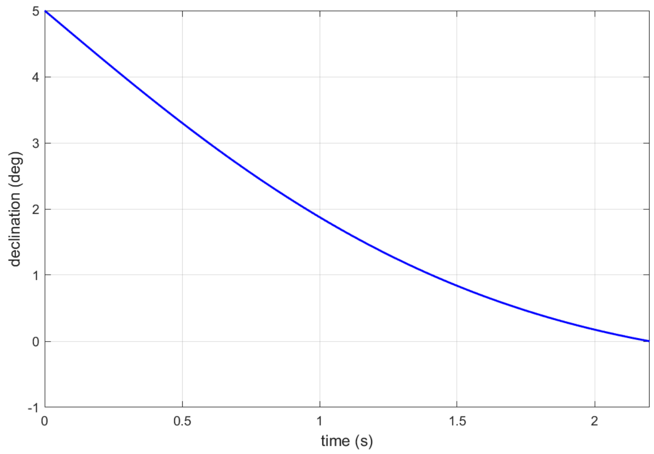

Figure 7. Graph of primer and cartridge case hole center offset angle variation

From the comprehensive simulation analysis results, it can be seen that the selected impedance parameters can ensure rapid convergence of the misalignment angle while maintaining stable contact force. This provides a parameter reference for actual primer pre-tightening operations and offers a theoretical basis for the robot to achieve high-precision and safe operation during the assembly process.

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5. Conclusion

This paper addresses the problem of thread damage that can easily occur due to alignment deviations during the assembly of primer and shell threads in a surface-source interference projectile. A compliant pre-tightening method based on position-based impedance control is proposed. A position-based impedance control model is established, mapping contact force deviations into end-effector pose corrections through the impedance controller, achieving coordinated force and position control during the primer pre-tightening process. This control strategy uses position control as the inner loop, while the outer loop corrects the desired trajectory through force error, making it relatively simple and suitable for precision assembly scenarios with small contact force and displacement. The effects of inertial parameter M, damping parameter B, and stiffness parameter K on the system's dynamic response are analyzed through simulation. The results show that M mainly affects the system's overshoot and regulation time and should be chosen small, B mainly affects overshoot and response speed and should be chosen large without increasing response time, and K has an opposite effect to B and should be chosen large without causing overshoot. Through parameter influence analysis and simulation verification, a set of impedance parameters suitable for primer pre-tightening was obtained, and the pre-tightening process was simulated under a 5° initial axis angle deviation. The results indicate that the position-based impedance control method can correct the deviation angle to near 0° within 2 seconds while maintaining the contact force stable at around 6 N, effectively preventing thread damage. This provides a theoretical reference for practical robotic assembly systems.

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