Design of Direct Teaching Behavior of Collaborative Robot Based on Force Interaction

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***Abstract*— Direct teaching can help users without the expertise of robots to quickly program a robot and plan trajectories in a complex environment. It is one of the typical applications of human-robot cooperation for improving production efficiency. However, the existing direct teaching system and related research have the problem that the human-robot communication is not intuitive enough, and the personnel safety in the teaching-playback process cannot be fully guaranteed. Based on the self-developed torque-controlled robot platform, we propose a force interaction method to achieve natural command communication. Then, combined with the analysis of the security threats in the operation process, a proper behavior of the direct teaching robot is designed to form a complete teaching-playback strategy. The proposed force recognition method and direct teaching behavior are verified on a 7-DOF collaborative robot.**

***Index Terms*— Direct teaching, robot programming, human-robot cooperation, collaborative robot**

I. INTRODUCTION

Teaching-playback is an intuitive programming method for robot, and it is one of the most commonly used programming methods in practice [1]. With this method, the human worker needs to give the position and velocity data of each track point during the first motion of the robot, and then the robot performs the operation according to the recorded data. Thus, the premise of playback is to obtain a teaching trajectory containing a sequence of positions [2]. In current industrial applications, the teaching of industrial robots is mainly assisted by an auxiliary equipment, called a teaching pendant. However, since the human user holding the teaching pendant and the robot are in different coordinate systems, this programming method requires the user to master specific skills on robot kinematics. The implementation of direct teaching can make the teaching process more convenient [3, 4]. In the sharing workspace, the robot moves according to the force exerted by human, so that human intention can directly reflect on the movement of the robot. With this intuitive method, inexperienced users can also plan a certain trajectory by manipulating the robot. Therefore, the accessibility and efficiency of robot programming is improved.

According to the working state of the motor, direct teaching can be divided into two types: the power-off teaching, and the on-servo teaching [5]. When the power supply of the robot is cut down during teaching, each joint motor is in non-enable state, and the human user has to overcome the gravity and friction of the robot when moving it. This method is relatively easy to implement, however, since the industrial robot generally has a large weight and its joint actuators have large friction, the power-off teaching is generally laborious. In addition, under the disturbance force, it is difficult for human users to position the robot to an accurate teaching point. In view of the above problems, the on-servo teaching is widely used, that is, a multi-dimensional force/torque (F/T) sensor with a handle is attached at the end of the robot to sense the human's teaching force, and then the robot generates position command from the teaching force according to the admittance control. Therefore, this method is unaffected by the internal force of the robot mentioned above [6], and it is well adapted to existing industrial robots. However, due to the need for additional auxiliary equipment, the cost for implementation is increased and the load capacity of the robot is reduced. Limited by the force sensing area, only 6 degrees of freedom at the end of the robot can be programmed; for redundant robots with more than six joints, this method is not applicable. In addition, due to the inherently high stiffness of industrial robots, there is a great risk involved when the human is in direct contact with the robot. Force-free control can provide an ideal condition for direct teaching and it is therefore widely studied [1, 7, 8]. With the variable stiffness controller, the joint stiffness parameter k_j is

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set to zero, and the robot can enter a zero-force state, with gravity-free and friction-free characteristics. In this state, the human can move the robot without effort according to the predetermined path. Compared to the solution with force detection in the end-effector, the robot under force-free control exhibits compliance at all joints, making human-robot interaction more safe. Human users can manipulate individual joint to shape the robot's configuration and therefore take advantage of its redundant freedom to achieve a more flexible workspace. This method can be applied to any robot with torque-based controller without the need for additional accessories. The force-free robot cannot hold its position through closed-loop control, so it is prone to be affected by disturbances other than the teaching force, and drifts without human constraint. In order to solve this problem, the collaborative robot generally includes a special button on its body or the teaching handle to switch on the force-free mode [7, 10] (Fig. 1). The robot enters the zero force mode only when the human presses this button; otherwise, the robot remains locked.

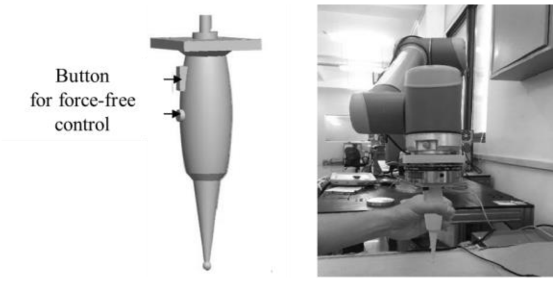

Fig. 1 The button on the teaching handle is used to activate the force-free state [9]

This solution can effectively reduce the risk of accidental drift of the robot, but requires additional hardware and operating procedures. This study provides a more natural way for instructing robots that is in the same way that human would instruct his partner. So far, this is not possible for industrial robot [10]. Base on the proprioceptive force perception, the robot is able to collect and analyze the external force given by human. When the force signal conforms to a specific pattern, the robot will switch to force-free state; when this pattern is detected again, the robot will return to the locked state. The force pattern selected here is a double-tap: the operator can unlock or lock the robot by tapping the same part of the robot twice in a short time. In order to distinguish the pattern force and other contact forces more accurately, we propose a multi-faceted discriminating condition based on the analysis of direct teaching.

Direct teaching means that the human physically interacts with the robot and move the robot by manipulating its body while poses the fundamental problem of how to ensure personnel safety in any cases [11-13]. In order to ensure safety, if the robot detects a collision when following the teaching trajectory, it should immediately stop the current movement and decrease its stiffness to reduce the risk of squeezing. After the threat is removed, the robot is supposed to restart under the direction of the human. In this work, we propose a systematic solution for direct teaching of collaborative robots. The key technologies include the recognition of pattern force for human instruction and the behavior design of robots in both teaching and playback phases. Through the implementation of these methods, safe and efficient direct programming and playback can be realized without any additional hardware. This paper is organized as follows. Section 2 introduces the hardware composition of the system and the relationship between each functional module. Section 3 describes the principle and implementation of pattern force recognition. In Section 4, the behavior of the robot in teaching and playback stage is designed based on the analysis of safety issues. Finally, we tests the proposed behavior through experiments in Section 5.

II. PROBLEM STATEMENT AND SYSTEM DESCRIPTION

The direct teaching system consists of a human user and a robot that implement programming through the interaction of force and motion. From the perspective of the robot, the contact force felt during the collaboration process can be summarized into three categories.

1) Accidental force. It indicates the external force results from accidental contact between human and robots during teaching and playback. Accidental forces on a robot with force-free control can cause unexpected drift in position, posing a safety hazard. In the stage of playback, the appearance of accidental force means that the robot collides with human or the environment.

2) Pattern force. The force that the operator actively apply to the robot in order to convey an instruction during the teaching or playback process. This type of force usually conforms to a certain pattern to facilitate robot recognition.

3) Demonstration force. It refers to the force exerted by human during teaching to generate a target trajectory. With force-free control, small teaching force is enough to make robot move. Since the inertia of the robot body limits its response speed, the effective demonstration force generated by human tends to change slowly.

These contact forces may have different effects on human-robot interaction when the robot is in different states. They can affect the efficiency of programming, and may bring threats to the safety of human and workpieces. Therefore, it is necessary to take all possible situations into consideration and design the robot behavior on this basis.

In this study, the robot system consists of three parts: the robot interacts physically with human, measures the state variables of the robot and feed back to the controller as shown in Fig. 2. The controller is used to implement variable stiffness control and estimates contact force based on the torque sensing in each joint. This information is then uploaded to the host computer. the host computer communicates with the controller by Socket, recognizes the pattern force from other contact forces, determines the state of the robot, and then generates an appropriate behavior to be transmitted to the controller for execution.

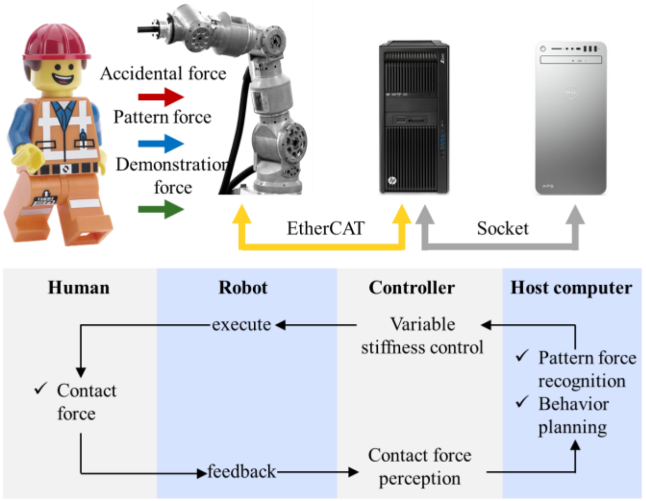

Fig. 2 The hardware structure and connection of the direct teaching system

Here, torque-based variable stiffness control is the basis of direct teaching for robot. Its principle is to switch between position control, compliant control and force-free control by adjusting the feedback gain in position loop from large to small and then to zero. The controller is implemented by a cascade structure as illustrated in Fig. 3: the inner loop is used for closed-loop torque control with negative velocity feedback to damp the joint motion; and the control law of outer loop is a proportional-differential (PD) controller with gravity compensation.

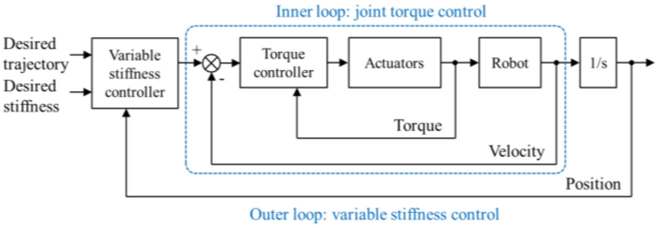

Fig. 3 A cascade controller for robot variable stiffness control

III. PATTERN FORCE RECOGNITION

The pattern force is used to convey the instructions of human to the robot to trigger a specific action. The prerequisite for the robot to receive the instruction successfully is the ability to identify the pattern force from other contact forces. The difficulty of pattern force recognition lies in the variety of physical interaction between human and robot. People and robots always have intentional or unintentional force interactions, which results in various contact force signals. In order to distinguish, which comes from the intentional contact and which are mistake among these signals, a comprehensive analysis of the direct teaching process is needed.

A. *Pattern force recognition in locked state*

When the robot is locked, it is expected to be enabled by the input of the pattern force stemming from specific pattern of human one-hand taping in any part of its body. At this time, the disturbance signal mainly comes from the accidental collision or extrusion by human, and the corresponding signal of contact force usually presents a peak or trapezoidal contour. Here, "double tap" is chosen as the pattern of informative force to distinguish from the disturbances, that is, the peak in contact force signal appears twice in a short time. Similarly, the robot in force-free state need to distinguish between teaching force and pattern force, while the former is usually a smooth signal. So that the double-tap pattern can also be effective.

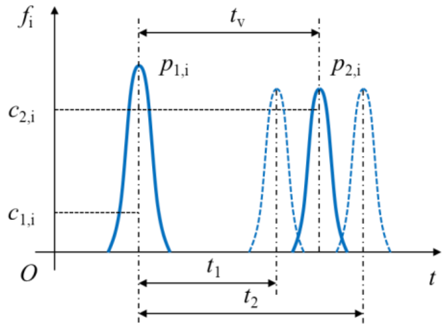

Fig. 4 Contact force signal of the double-tap pattern

In order to make the recognition more accurate, the adjustment of the pattern parameters and the determination of the relevant state are indispensable. The parameters of the double-tap pattern recognition include the contact force parameters $c_{1,i}$, $c_{2,i}$ and the time parameters t_1, t_2, where i = 1, 2, ..., 7 is the joint number of the robot. In Fig. 4, $p_{1,i}$, $p_{2,i}$ represent the two peaks of the force signal (absolute values) respectively generated by the double tap, and t_v represents the time interval of the two taps. The prior threshold value $c_{1,i}$ is used to exclude the noise of the torque sensor and other small disturbances, and it is designated to strike a balance between sensitivity and correctness for specific hardware. For those contact force signals exceeding those thresholds, the peak $p_{1,i}$ and the moment of its occurrence is recorded.

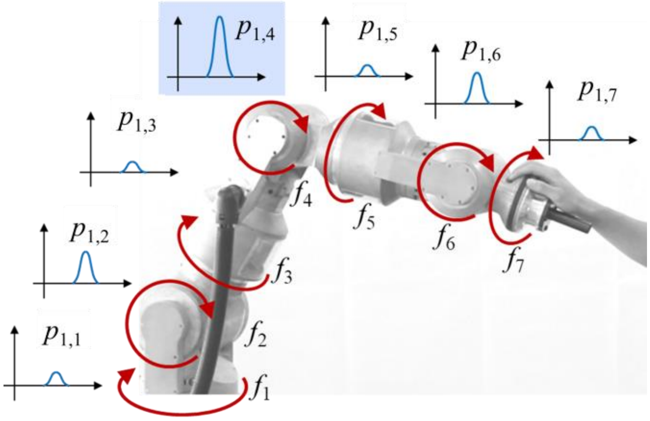

Fig. 5 The force signal in each joint of the robot under a single tap

Due to the different configurations of the robot and the position of the human touching it, the force joint torque sensed by each joint of the robot is also different. Fig. 5 illustrates the varied signals resulting from a single touch. Selecting a joint with a significant change in contact force for pattern force sensing can effectively improve the signal-to-noise ratio of the algorithm, thereby improving the recognition accuracy. For the double-click pattern, the human's two consecutive tap are always in the same position on the robot body with the same direction, and similar force. Therefore, when the first peak of contact force appears, the joint with the maximum ratio r_i =

$p_{1,i}/c_{1,i}$ can be selected as the *receptor joint*. Without loss of generality, it is assumed that Joint k is a receptor joint, and then we focus only on this joint. In general, the actuator at the joint of the robot is flexible, so the robot body can be represented by a multi-rigid system that will resonate under the excitation of external forces. Even if only one tap occurs, multiple spikes will arise after $p_{1,k}$ due to oscillation, which can interfere the recognition of the second tap $p_{2,k}$. The solution here is to determine the $p_{2,k}$ by using the time interval $[t_1, t_2]$ and the threshold $c_{k,2}$. Constrained by the sports system of human, the time interval between two taps always lies in a limited range. Referring to the double-click interval of a PC mouse, this interval is generally 100-300 ms. In this way, the spikes outside the time interval are excluded from being $p_{2,k}$. On the other hand, based on the fact that the peaks of the resonance spikes are attenuated according to the damping ratio of the system, the interference signals can be further eliminated by setting a confirmed threshold $c_{2,k}$. If the signals in interval $[t_1, t_2]$ are smaller than $c_{2,k}$, the robot is considered not to receive the second tap; otherwise, it is confirmed that the double-click pattern is recognized. $c_{2,k}$ is determined by the following relationship

$$c_{2,k} = a\ p_{1,k}. \tag{1}$$

Where the scale factor a should be larger than the attenuation rate of the system resonance amplitude.

B. *Pattern force recognition in force-free state*

The above algorithm can work well in locked state, while when the robot is in force-free state, the teaching force from human will make the situation more complicated. Due to its redundant joint, direct teaching of such robot manipulator generally requires both hands of the human operator holding to the end-effecter and another link of the robot body respectively. The hand designating the desired end-effecter position of the robot is defined as the primary hand and the other shaping the robot to required configuration is called the auxiliary hand. Because of the significant inertia of the robot body and the damping design in joint torque controller (see Fig. 3), the robot free from operators' domination can remain motionless in a few seconds before floating away so that occasional release of the auxiliary hand during teaching is allowable. In this sense, the operator is able to give pattern force to the robot by the auxiliary hand while maintain the position of its end-effecter with the primary hand. The reciprocating teaching force may be mistaken for a double-click pattern, causing the robot to respond incorrectly. It is therefore necessary to add more constraints to the decision conditions. According to observations from practical direct teaching, the person usually reduces the operation speed of the robot to zero before ending the teaching, and gradually reduce the strength for gripping the robot. From the robot's point of view, before the input of pattern force, the joint speed and contact force have been reduced to zero and maintained for a period, while this situation rarely occurs during teaching. Therefore, the determination of the 'zero speed' and 'zero contact force' conditions is added to the double-click identification method, which forms a complete pattern force recognition algorithm as summarized in Table 1.

Table 1 Pattern force (double-tap) recognition algorithm

Algorithm 1

```
flag_pattern = False
if $\int_s$ norm($\boldsymbol{v}$) d$t$ < $e_v$ and $\int_s$ norm($\boldsymbol{f}$) d$t$ < $e_f$ then
  $p_{1,i}$ ← peak_detection
  if max $_i$ ($p_{1,i}$/ $c_{1,i}$) > 1 then
    k = argmax $_i$ ($p_{1,i}$/ $c_{1,i}$)
    $c_{2,k}$ ← $a$ $p_{1,k}$
    $t_v$ ← set_timer
    while True then
      if $t_v$ < $t_2$ then
        $p_{2,k}$ ← peak_detection
      else
        return False
      end if
    end while
    if $p_{2,k}$ > $c_{2,k}$ and $t_v$ > $t_1$ then
      return True
    end if
  end if
end if
return False
```

Where $\int_s$ denotes the integral of variable over the time interval s, and e_v and e_f are the thresholds for the determination of 'zero speed' and 'zero contact force' conditions, respectively. In an actual system, this algorithm is cyclically called to query the force interaction state. It should be noted that if $p_{2,k}$ is not detected in a certain period after $p_{1,k}$, the detection algorithm will be considered as a time out and reset. The parameters in the proposed algorithm need to be determined through experiments. Take our self-developed cooperative robot DCRA as an example. The parameter selection is shown in Table 2.

Table 2 Parameter selection of the recognition algorithm

parameter	value
$\{c_{1,i} \| i=1, 2, \ldots, 7\}$	[8, 8, 4, 4, 2, 2, 1] Nm
a	0.99
$[t_1, t_2]$	[0.1, 0.3] s
s	0.1 s
e_v	0.5 °
e_f	0.5 N·s

In the actual system, the host computer exchanges data with the robot controller at a frequency of 100 Hz, and cyclically calls the above recognition algorithm to query whether the double-click pattern is detected. Therefore, numerical integration is actually used in the determination of zero speed "and" zero contact force conditions. The integration step is 0.01 s.

C. *Experiment for double-tap pattern recognition*

In order to verify the proposed recognition algorithm in both locked state and force-free state, we design an experiment as follows. The robot is locked initially and will switch between the locked state and force-free state if a double tap pattern is detected. The contact force, velocity, and activation state of the pattern force in joint space are recorded during the experiment.

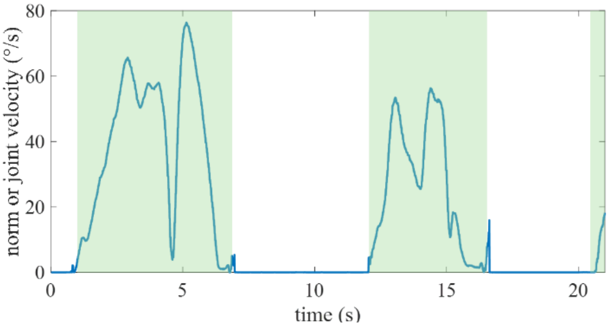

Fig. 6 Norm of joint velocity vector with 7 joints

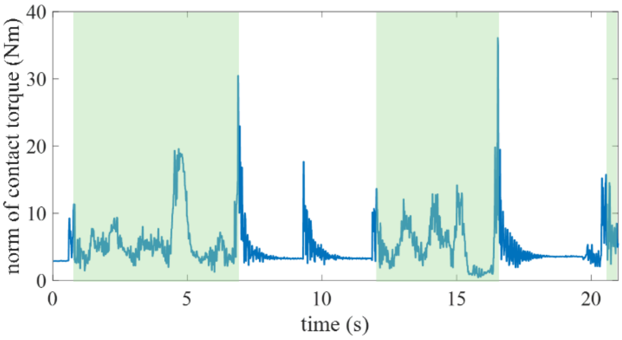

Fig. 7 Norm of contact force

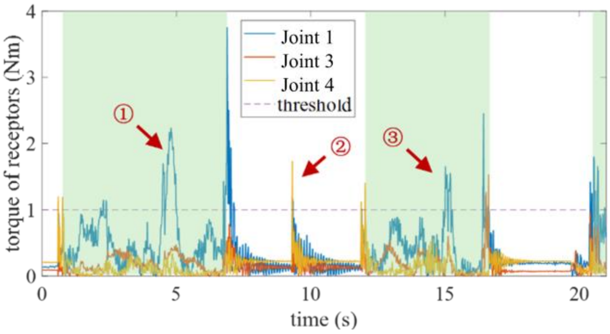

Fig. 8 Force signals of the receptor joints

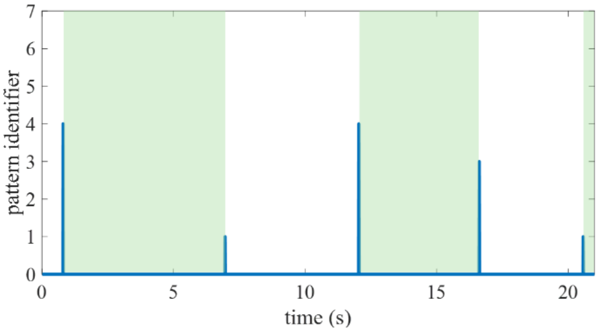

Fig. 9 Activation state of the double-click pattern

Fig. 9 shows the activation state of the double-click pattern. When the pattern is not activated, this identifier will display zero. When the double-tap pattern is activated, the indicator will display the number k of the receptor joint. In the experiment, Joint 4 firstly detected the double-tap pattern as a receptor joint, so the robot switch to force-free state (indicated by the shaded part). Under the teaching force of human, the robot starts to move and the joint velocity increases (Fig. 6). In this phase, the human deliberately change the teaching trajectory quickly, resulting in a bimodal signal that is similar to the double-tap pattern (Arrow 1 in Fig. 8) of the contact torque to verify the robustness of the recognition algorithm. Another pseudo-double-tap signal also appears in the subsequent force-free interval (Arrow 3 in Fig. 8). As shown in Fig. 7, the robot experiences a rapid deceleration and acceleration process under the sudden change in teaching force (Fig. 6). Therefore, these two states violate the "zero contact force" condition at least, so the double-tap pattern will not be activated. When the velocity of the robot is reduced by human and the teaching grip is relaxed, the double-tap pattern applied by human is successfully recognized by Joint 1, thereby making the robot to re-enter the locked state. Then, the human operator tried to make a single touch to the robot (Arrow 2 in Fig. 8). From the contact force signal, it can be seen in Fig. 7 that the robot body has obvious resonance. As expected, this signal cannot pass the double-tap check, so the robot keeps its original state. Until Joint 4 detects the pattern force, the robot switches from locked state to force-free state. In the rest of the experiment, Joint 3 and Joint 1 detected the double-tap pattern as receptor joints, respectively, which realizes the basic function of switching the robot state through force interaction.

IV. BEHAVIOR DESIGN FOR DIRECT TEACHING

In the process of teaching and playback, in order to achieve an efficient human-robot cooperation while ensure safety, it is necessary to systematically design the behavior of the robot, that is, to summarize the possible states of the robot and determine the conditions for transition between these states. This section first analyzes the security threats that robots may bring during direct teaching. Then, based on the safety criterion, the robot behavior in both the teaching and playback phases is designed by means of the finite state machine (FSM).

A. *Safety threat in direction teaching*

In direct teaching, human and robot share the same workspace and have frequent physical interactions, thus bringing security issues that is not encountered in traditional industrial robot applications. In teaching stage, in order to facilitate traction, the robot under force-free control only has a small damping, so “drift” will occur without human constraint. The robot may uncontrolledly change its configuration, acceleration, and collide with human or its surroundings in the operating space. Therefore, it is necessary to limit the activation conditions for the force-free state strictly.

During the playback phase, the robot will move according to the teaching trajectory in position control mode, where its workspace still highly coincide with that of human. Since the robot movement may have a large rigidity and velocity at this time, it potentially has a large destructive force when impacting with human, so it is necessary to design a complete reaction strategy for the accidental collision, and avoid the secondary injury caused by the reaction behavior.

B. *Robot behavior in the teaching phase*

During teaching, the robot mainly switches between two states: force-free state and locked state. The force-free state is the key to realizing direct teaching, in which the robot can be dragged by human and simultaneously records the experienced track points. After the teaching of this paragraph, the operator sends a command to the robot through the mode force to switch to an auxiliary state, the locked state, thus avoiding uncontrollable movement under accidental contact and disturbances. At the same time when the robot enters the locked state, the recorded trajectory is filtered and stored in a local directory of the host computer. The filtering used here is a simple median filtering to eliminate the influence of the unsmooth trajectory caused by the vibration of human hand during teaching. The above behavior can be expressed as a finite state machine as shown in Fig. 10.

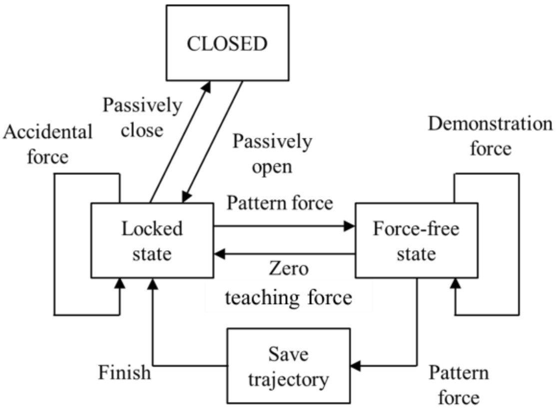

Fig. 10 Robot behavior in the teaching phase

After the robot starts from the state ‘CLOSED’, it is locked at first, i.e., it remains stationary with high feedback gain in position loop. In this state, the contact force can be divided into two categories: pattern force and accidental force. The pattern force is a contact force signal that coincide with the recognition condition of double-click pattern; while the accidental force indicates other external forces other than the pattern force. The robot will keep itself locked under the accidental force. Only when it receives the pattern force signal from human, the robot switch to the force-free state and get ready to record the teaching trajectories. In the force-free state, the contact force is divided into pattern force and teaching force, which are distinguished from each other by the pattern force recognition algorithm. The robot will maintain its current state under continuous teaching force until it receives the pattern force, or feels no effective teaching force for a period (1 s), then it returns to the locked state and saves the experienced trajectory. Wherein the detection of zero teaching force is used to cope with the accidental departure of the human during teaching and subsequently prevent the robot from unconstrained movement state.

C. *Robot behavior in the playback phase*

After teaching, the robot can repeatedly run the recorded trajectory. In each recurrence, the robot behavior mainly includes ‘back to the starting position of trajectory’ and ‘track trajectory’ as shown in Fig. 11. The former is the prerequisite of the latter. In addition, because collaborative robots typically work in complex human environments, they need to react properly to unexpected disturbances. This study focuses on robot collision detection, post-collision reaction strategies, and task restarting. Here, the robot behaviors for safety purpose include ‘emergency stop’, ‘compliant state’ and ‘request human to remove obstacles’.

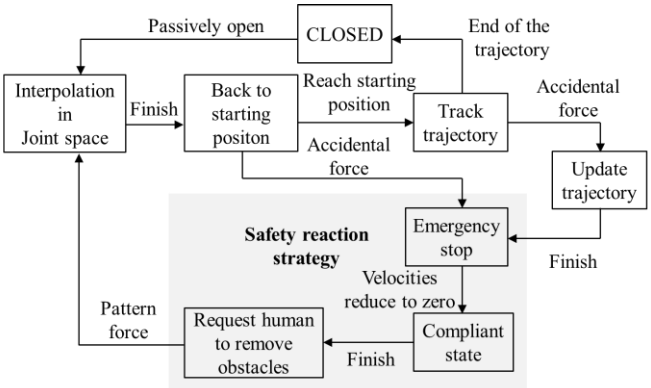

Fig. 11 Robot behavior in the playback phase

Prior to trajectory tracking, the robot must move from the current position to the starting point of the teaching trajectory. Strictly speaking, this is a trajectory planning problem, and an optimal trajectory can be found by planning algorithms. However, due to the uncertainty of the environmental, the robot cannot obtain the constraints necessary for online planning. Therefore, the solution here is to use a simple linear interpolation in joint space to generate a trajectory from the current position to the starting point. It relies on a safety reaction strategy to eliminate the obstacles that may be encountered during operation.

The safety reaction strategy can be activated by any contact force that exceeds a preset threshold. It consists of three intermediate states. The first one is the emergency stop. The robot controller will output maximum allowable current whose direction is opposite to the velocity at each joint, and reduces the robot to zero as soon as possible. This process is not governed by the variable stiffness controller and it can be understood as a process that uses damping to dissipate the kinetic energy of the robot. With the reduction of kinetic energy, the threat of robots to the environment is basically eliminated. However, robots in an emergency stop are still likely to invade the space of human or the environment continuously, which can cause squeezing injury and obstruct site cleaning. Therefore, in the designed behavior, when the joint velocity is reduced to zero (the norm of the velocity vector is less than a small value), the robot is expected to become compliant and yield to an external force to eliminate squeezing. To achieve active compliant control, the variable stiffness controller will retake the robot. On the other hand, force-free control is not suitable in this case, because the motion of the robot without position feedback control will become unpredictable and may cause secondary damage. Therefore, a better strategy is to adjust the position gain to a small, non-zero value and set the equilibrium position to the current encoder reading. As a result, the robot in compliant state becomes a low-stiffness damper spring, and the controller will make a sound to ask human to clear the obstacle. Obviously, this is very easy for a human operator. When the security threat is eliminated, the operator can restart the operation by double-tap. Then the robot will regenerate a trajectory back to the starting point of the trajectory.

When the robot reaches the starting point of the trajectory, it begins the trajectory tracking when the robot will move in accord with the exact trajectory demonstrated by the operator. In addition to trajectory tracking, the designed teaching framework also offer a via-point programming mode that can automatically plan a trajectory from the start point to the end point with linear interpolation in joint space. This mode is especially useful for single-point positioning and it is implemented simply by substituting ‘Track trajectory’ by ‘Spline interpolate and move’ in Fig. 11. In the absence of interference, the robot will follow the teaching trajectory to the end and complete the playback operation. If accidental force is detected during trajectory tracking, the robot will switch to safety reaction state, as described above, while the teaching trajectory will be updated for future rescheduling. The method to update the trajectory is to erase the track points that have been executed, so that the break point becomes the starting point of the new trajectory. When the threat is removed by the safety reaction strategy, the controller will generate an interpolation trajectory from the current location to the starting point of the new trajectory.

V. EXPERIMENT OF DIRECT DEMONSTRATION

In order to verify the effectiveness of the proposed robot teaching-playback strategy, the following experiment is designed in the context of actual human-robot collaboration. During the teaching phase, the human operator grip the robot to move in a simple trajectory. The general shape of the trajectory is a counterclockwise spiral with its centerline parallel to *z*-axis (Fig. 12).

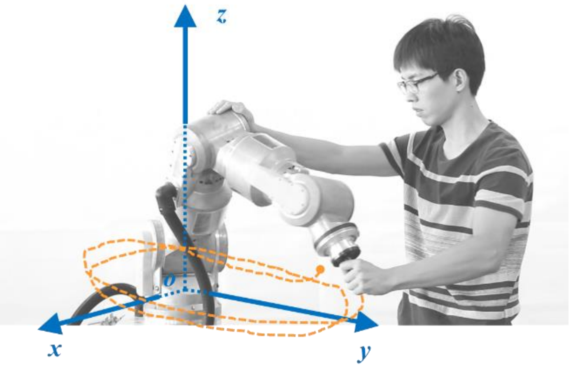

Fig. 12 The human operator programs the robot by physical demonstration with his two hands

Since our robot has 7 degrees of freedom, the human operator is required to guide the robot end with one hand while adjust the redundant degree of freedom of the robot with the other. In replay, the robot first moves from the teaching ending position to the starting point of the trajectory and then starts trajectory tracking (Fig. 13 (1)). This moment is marked as Time 1 (Fig. 14, Fig. 15). Next, at Time 2, the robot collides with human (Fig. 13 (2)), resulting in a spike in the contact force signal (Fig. 14). Emergency stop is triggered by the collision, and consequently the velocity of the robot is reduced to zero (Fig. 15). Then the robot enters the compliant state. At Time 3, the human tries to push the robot away to eliminate squeeze (Fig. 13 (3) (4)).

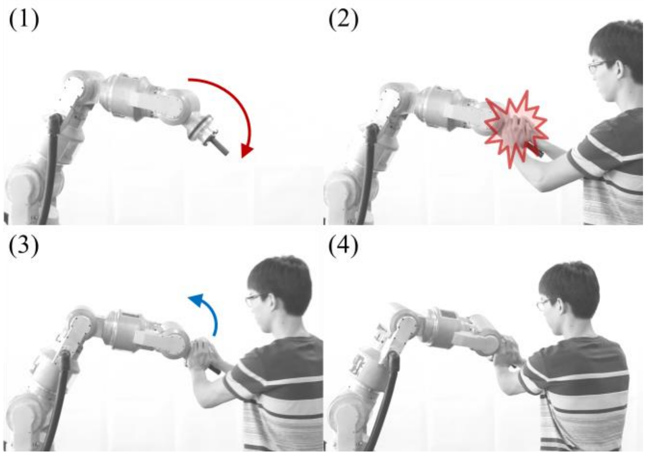

Fig. 13 The behavior of the robot in replay. 1) Trajectory tracking. 2) Collision with the human operator. 3) Switch to compliant state after collision. 4) The robot yield to external force.

From Time 3 to Time 4 in Fig. 14 and Fig. 15, we can see that the robot has a displacement proportional to the external force; at Time 4, when the external force disappears, the robot returns to its equilibrium position and waits for restarting. After eliminating the interference, at Time 5, the human activates the robot by double-tap. As can be seen from Fig. 14, Joint 2 recognize the pattern force as the receptor joint and inform the robot to continue the trajectory tracking. Until Time 6, the robot reaches the end of the trajectory.

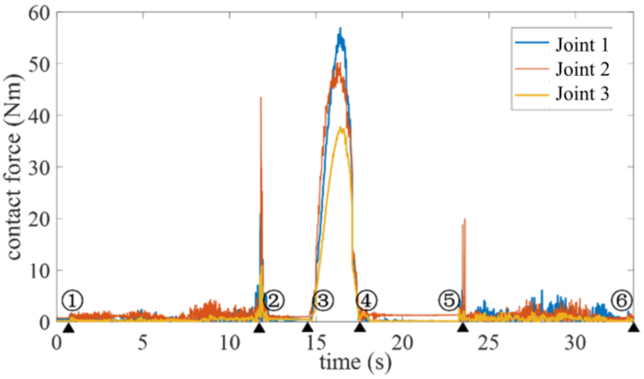

Fig. 14 Contact force (absolute value) at Joint 1, Joint 2, and Joint 3 during replay

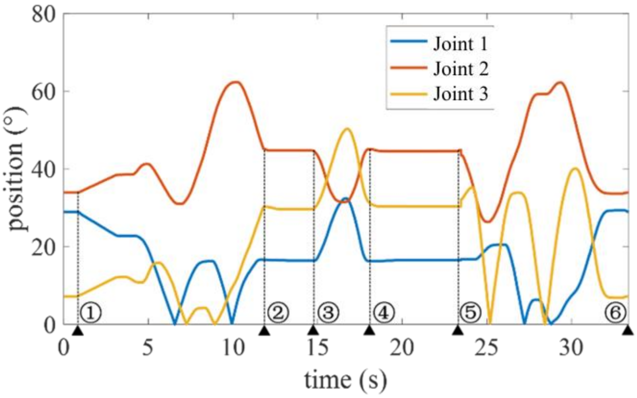

Fig. 15 Trajectory of Joint 1, Joint 2, and Joint 3 during replay

The behavior of the robot and the events that trigger the behavior during this experiment are summarized in Table 3. It is obvious that in the actual playback stage, the robot is able to handle the accidental collision according to the designed reaction strategy, and ensure the safety of robot-human interaction.

Table 3 Robot behaviors in replay and the events to trigger them

time	event	behavior
0	Passively open	
0 ~ ①		Back to starting point
①	Reach starting point	
① ~ ②		Trajectory tracking
②	Collision	Emergency stop
② ~ ③	Velocities reduce to zero	Go to compliant state
③	External forces	Yield
③ ~ ④		Displacement proportional to force
④	External forces diminish	Back to equilibrium position
④ ~ ⑤		
⑤	Double tap	restart
⑤ ~ ⑥		Trajectory tracking
⑥	End of the trajectory	stop

The teaching trajectory of the end-effecter from the human and the playback trajectory of the robot are shown in Fig. 16. The obvious deviation in the playback trajectory is due to the yielding motion of the robot under the external force from the human. It should be noted that this work is not going to investigate the trajectory tracking accuracy, so the stiffness used for playback motion is low. The maximum tracking error is 5 mm. As the stiffness in position feedback loop increases, the error will decrease.

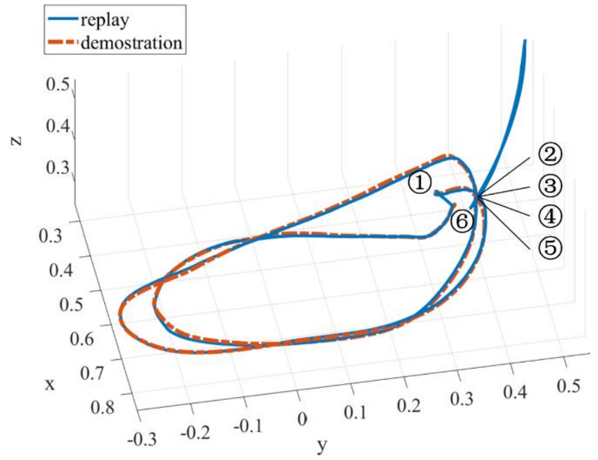

Fig. 16 Teaching trajectory and replay trajectory

VI. CONCLUSION

Motivated by the requirement of safe and natural interaction between human and collaborative robot, this study systematically designs the behavior for a direct teaching robot. Firstly, a force interaction method is proposed to realize intuitive instruction transition from human to robot, and the pattern force recognition method is designed to extract the pattern force from disturbances. Based on the recognition of the pattern force, the behavior of robot in the teaching phase and the playback phase is further designed by means of finite state machine to meet the safety requirements. The effectiveness of this behavioral strategy is verified on a 7-DOF collaborative robot.

In the following work, the environment model is acquired in real time in the track recurring part combined with visual feedback to realize non-contact avoidance and set-up operations, and further improve the security level of human-machine cooperation.

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