Remote Human-robot Collaborative Impedance Control Strategy of Pharyngeal Swab Sampling Robot

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Abstract—**Pharyngeal swab sampling, as an essential link in the detection of COVID-19, is characterized by the large task volume and susceptibility to infection. Therefore, it is necessary to use medical robots for remote sampling instead of in-situ sampling. However, on one hand, due to the influence of network delay, it is difficult to guarantee the closed-loop performance manipulated remotely by medical practitioners. On the other hand, the sampling process controlled by the robot independently is not always successful due to the inaccuracy of the planned trajectory caused by the sensors or the moment of the patients. To solve the problems discussed above, this paper proposed a remote human-robot collaborative strategy based on impedance control method, which can integrate the experience of medical practitioners into the automatic sampling process. During the sampling process, when the inaccurate scanning trajectory is detected, the medical practitioners can correct the planned trajectory on line according to the sensor information and the reaction of the patients. Then, the cooperative robot tracks the adjusted planned-trajectory based on the impedance control method and ensure that the contact force of sampling is maintained within a reasonable range. The simulation results show that the proposed human-robot collaborative strategy is effective taking the advantages of both medical practitioners and robots which can deal with the trajectory tracking problem caused by the inaccurate sampling of patients.**

Keywords—Pharyngeal swab sampling, Human-robot collaboration, Trajectory correction, Impedance control

I. INTRODUCTION

With the outbreak of COVID-19 all over the world, nucleic acid testing, as the most commonly used method of tests for COVID-19, has made great contributions in medical treatment, and throat swab is the most important sampling method. In the process of throat swab sampling, the medical staff must be in close contact with the patient. The patient coughs and breathes hard, which can produce a large number of droplets or aerosols, and has a high risk of cross infection. Therefore, the medical staff need to wear protective clothing when collecting throat swab. The work of the medical staff, who wear impermeable protective clothing to take throat swabs for everyone, is very intensive due to the hot and stuffy sun. Therefore, there is an urgent need to improve the working style of the medical staff. However, for the dangerous and unsuitable working space, such as underwater environment, nuclear environment and susceptible environment, teleoperation has become a research hot spot in the early stage [1]. Recently, Shenyang Institute of Automation, Chinese Academy of Sciences and Zhong Nan-Shan's team jointly developed a throat swab sampling robot system, consisting of a serpentine robotic arm, binocular endoscope, wireless transmission equipment and human-robot interaction terminal. And the team of Professor Sun Fu-Chun from the Department of Computer Science, Tsinghua University, combined with the research foundation of the self-developed flexible tactile sensor and multi-modal visual tactile perception method, designed and developed a set of robot prototype system for the autonomous sampling of pharynx swab, and applied for two invention patents[2-3]. Both of these robots are operated remotely by human within direct control.

At present, teleoperation is the most important method to control robot in the distance, as complete autonomy still has a long way to go. And remote human-robot collaboration methods have been suggested to facilitate teleoperation efficiency. Such as, an improved human–robot collaborative control scheme is proposed in a teleoperated minimally invasive surgery scenario [4]. With the assistance of sensors and models, the mapping from master hand to hand workspace is established, so that the operator can always keep control of the robot during the task execution [5-7].

While, the network delay in some cases influence the stability of the control system. Some theories have been proposed such as wave variables, scattering transformation to figure out this problem of low delay [8-9]. When the communication delay increases to several seconds or more than ten seconds, model prediction approach is proposed, with which sets up the remote environment and robot geometrical and dynamical model to receive the simulated visual and force feedback in real time [10]. Based on the model prediction, a human-robot collaborative semi-autonomous remote-control strategy is proposed to reduce operators' workload and enhance the operational accuracy [11]. But the acquisition of model parameters in model prediction is not easy and there are high requirements for human-computer interaction devices.

Whether the sampling process is controlled independently by robots or directly by medical personnel, it is difficult to guarantee the accuracy of sampling process due to the inaccurate predetermined trajectory caused by the sensor or the patient at any time and network delay. To address these issues, this paper proposed a remote human-robot collaborative strategy based on impedance control method, which can integrate the experience of medical practitioners into the automatic sampling process. And the trajectory tracking problem in robot sampling process is solved by on-line trajectory correction method, and the advantages of robots and humans are utilized to improve sampling efficiency.

The organization of this paper is as follows: Firstly, the process and strategy architecture of man-machine collaboration during pharyngeal swab sampling are described in section II. The strategy for trajectory correction is described in section III. Then the simulation is carried out in the fourth section. Finally, the conclusion.

II. REMOTE HUMAN-ROBOT COLLABORATIVE FRAMEWORK

In the process of sampling, human play an irreplaceable role to ensure safety and accuracy. In this section, we propose a scheme of human-robot collaboration in view of the human intervention needed in the whole sampling process.

Therefore, the indispensable human participation situations have been introduced during the sampling, see Fig.1. The framework shows the human-robot collaborative task assignment in the operation process. In the robot sampling process, the tracking problems are mainly caused by the imprecision of the sensor itself and the change of the position of the patients.

The trajectory deviation caused by the sensor is generally concentrated in the process of scanning the trajectory. Therefore, trajectory correction of this condition typically occurs when the swab begins to touch the posterior pharyngeal wall. Once the scanning trajectory is tracking, which is transmitted to human to determine remotely whether the trajectory is no problem. Then, the robot makes the motion in free space. When reaching the termination of free space, the robot's end effector might stay in front of or behind the target position due to the inaccurate scanning trajectory from the sensors. Through force feedback, the operator can judge the specific contact conditions and make corresponding modifications. Finally, the robot begins to perform constraint space motion based the sampling curve to wipe the back wall of throat.

As a result of stress or discomfort, the patient may take a corresponding adjustment of position in the process of sampling and the original track is no longer accurate. At the moment, human adopt relevant strategies to adjust the trajectory according to the feedback of the sensors and the action of the patient.

The online correction trajectory occurs in the above human-robot task allocation. As shown in Fig. 2, a collaborative mechanism has been proposed. In the mechanism, the medical practitioners' experience integrated into collaboration is a crucial point of our control strategy, which complements the capabilities of robots to perform changeable tasks in terms of accuracy and efficiency.

For the above scenario, the strategy mainly consists of two parts: trajectory correction algorithm and state flow. When a trajectory tracking problem happened, the medical practitioners modify and generate a new curve based on the "Scanning curve", which named " Doctor curve". Then a "Modified curve" is obtained by the weight analysis between the new curve and the initial curve via trajectory correction algorithm.

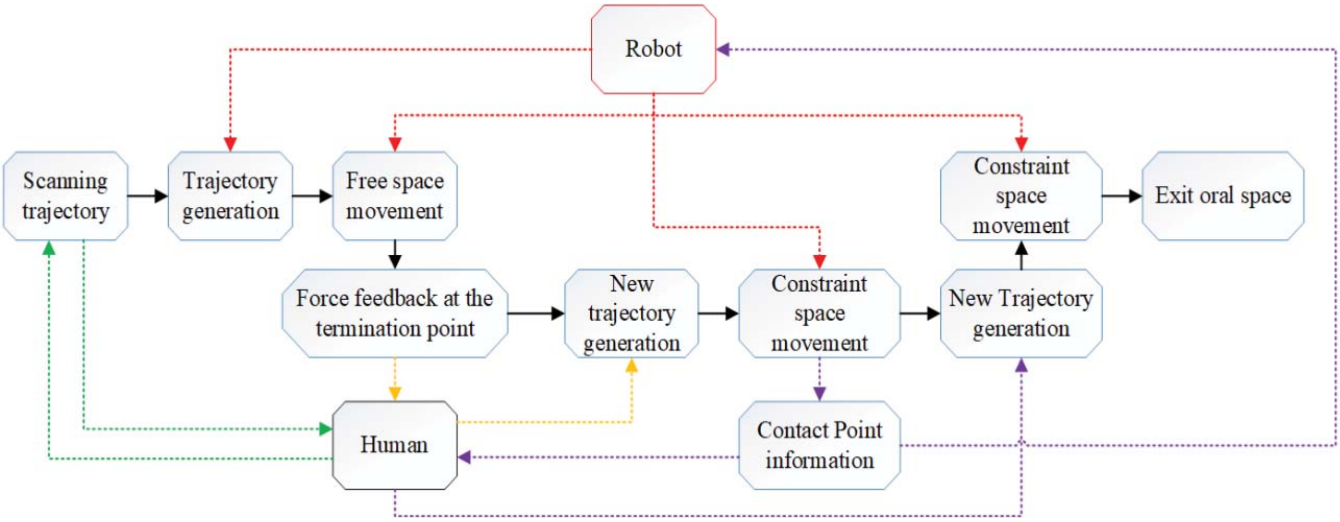

Fig. 1. The strategy of human-robot collaboration architecture

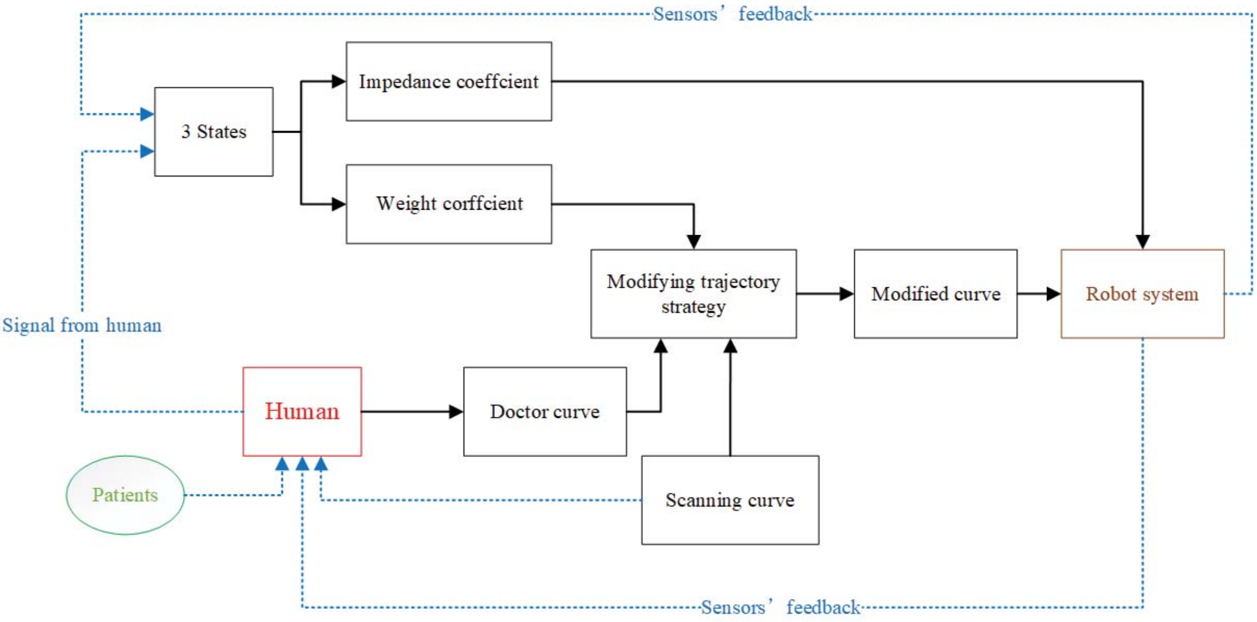

Fig. 2. Block diagram of the trajectory correction strategy

In the meantime, the state flow is used to output the weight coefficient and an impedance coefficient. Three different states are defined according to the different feedback information. There are three kinds of feedback: the end-effector force signal, position signal from visual acquisition and patient's feedback, respectively. Among the process, human make decisions through feedback, then the states are switched on the basis of judgment result.

III. ALGORITHM

A. *Negotiation state*

Three states are set to describe the situation of human-robot negotiation, which respectively expressed as Initial state (IS), Robotic state (RS) and Human modified state (HS). As shown in Fig. 2, the states are switched according to signal value ($Signal_h$) from operator and the end-effector force feedback (F_{feed}). In the IS, there is no contact force and the robot carries a motion in free space. And HS and RS mean that the adjustment is from human or robot. We set up four different negotiation standards S_1, S_2, S_3, S_4 follows:

$$Signal_h == 0, F_{feed} == 0 \qquad S_1$$

$$Signal_h == 1, F_{feed} == 0 \qquad S_2$$

$$Signal_h == 1, F_{feed} > F_{threshold} \qquad S_3$$

$$Signal_h == 0, 0 < F_{feed} < F_{threshold} \qquad S_4$$

By the signal from human and set appropriate force thresholds $F_{threshold}$, we apply S_1, S_2, S_3, S_4 to judge whether human intends to intervene. If S1 is triggered, the state is held as IS. In this state, the robot carries normally without the contact force in free space and the impedance coefficient of free space motion is provided. When S_2, S_3, S_4 are triggered, the trajectory tracking occurs in constrained space. And S_2, S_3 mean that human is aware of abnormal force feedback and modify the trajectory. With the trigger of S_4, robots carry the automatic sampling process.

B. *Trajectory modification strategy*

The trajectory tracking problem can be classified into two cases. On the one hand, there is deviation in the scanning trajectory, so the contact force at the sampling starting point be abnormal. On the other hand, the trajectory tracking problem is caused by the patients. The movement of the patients cause the original trajectory to become less accurate.

Based on the information of the sensors and the visual interface, the medical practitioners make the corresponding judgment, and then corrects it online on the original basis._To ensure that the corrected trajectory is closer to the modified trajectory, that is, to obtain the "Modified curve", the modified trajectory and the original trajectory need to be weighted average. The equations are expressed as in:

$$p = p_h * w_1 + p_0 * w_2 \tag{1}$$

Where p is the position of "modified curve", $p = [x, y, z]$. p_h, p_0 denote the position of "Doctor curve" and "Scanning curve", see Fig. 3. And w_1 is the weight value, $w_2 = 1 - w_1$.

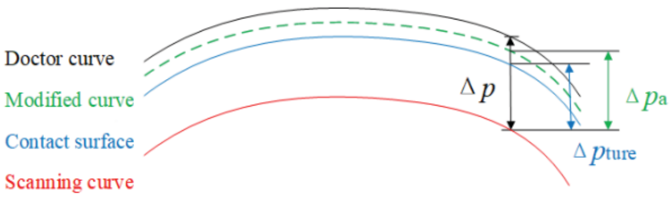

Fig. 3. Schematic diagram of trajectory correction process

The weight can be expressed as follow:

$$w_1 = \frac{\Delta p_a}{\Delta p} \tag{2}$$

Where Δp_a is the distance between “Modified curve” and “Scanning curve”, $\Delta p_a = p - p_0$. Δp is the distance between “doctor curve” and “Scanning curve”, $\Delta p = p_h - p_0$.

The weight value is not invariable, but selected according to the actual situation. After the robot starts sampling along the "Modified curve", once the end-effector touches the target surface, the weight value changes as follow:

$$\begin{cases} \Delta p_a = \Delta p_{ture} = p_{ture} - p_0 \\ w_1 = \frac{\Delta p_a}{\Delta p} \end{cases} \tag{3}$$

Where p_{ture} is the position of the contact point; w_1 is changed to make the tracking trajectory basically consistent with the actual contact surface.

C. *Force tracking control*

The trajectory corrected online by the medical practitioners is still deviated from the actual contact surface, see Fig. 4. When the end effector is scraped along the modified trajectory, some parts of trajectory may not be in contact with the pharynx posterior wall.

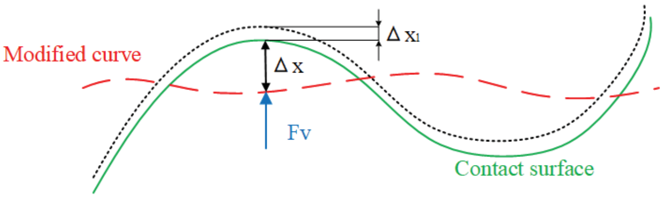

Fig. 4. Diagram of actual contact condition

To maintain constant contact and appropriate contact force during the sampling process, the contact force F_v is defined and expressed as:

$$F_v = f + F \tag{4}$$

Where f is the pre-tightening force which ensure the constant existence of contact force. F denotes the force and the corresponding desired trajectory modification Δx by the impedance controller. The common formulation for the target impedance is:

$$M\Delta\ddot{x} + B\Delta\dot{x} + K\Delta x = F \tag{5}$$

Where M, B, K are the mass, damping, and stiffness matrices of the target impedance.

In [12] and [13], there exist contact models based on viscoelasticity, which are proven to effectively estimate the interaction of the soft contact. The models yield better results when there exist hard impacts or high velocities involved in the direction of penetration. The received model is expressed as:

$$F_e = F_v = K\Delta x_1 + D\Delta\dot{x}_1 \tag{6}$$

Where Δx_1 is the indentation depth, K and D are stiffness and damping coefficients, and F_e is the contact force associated with it along the surface normal.

IV. CASE STUDIES

In this section, the strategy proposed above is tested in MATLAB. In the simulations, we established a mathematical model to approximate the posterior pharyngeal wall, which is approximated by a hollow spherical ring. In terms of the simulation of trajectory deviation caused by this sensor, the given “Scanning curve” deviates from the contact surface. During the Human modified state, w_1 is equal to 0.8. We can get an initial correction trajectory. Then with w_1 is equal to 0.6, the initial correction trajectory is modified again when the Robotic state is switched. Fig. 5 gives the result of simulation base on above condition.

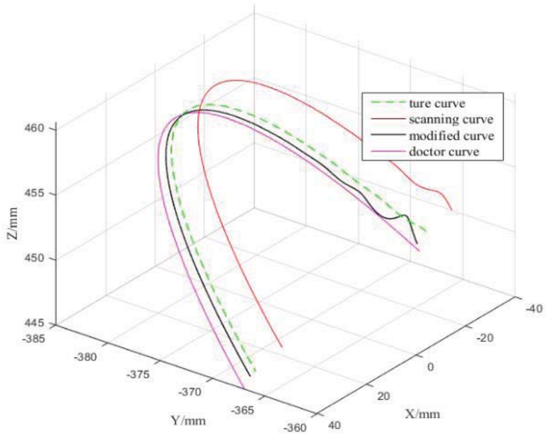

Fig. 5. Simulation curves of modified process

According to the modified trajectory and force tracking control, we can obtain the actual tracking curve and force in Fig.6 and Fig.7. When the robot tracks the trajectory, the value of is set as 2N. Due to the force’s mutation from free space to constraint space, the force tracking curve fluctuates at the moment of contact. And the contact force tends to be stable, and the value is equation to about 1.5N.

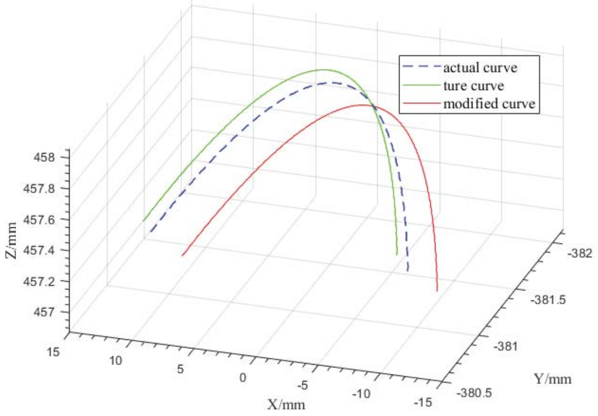

Fig. 6. Actual sampling trajectory

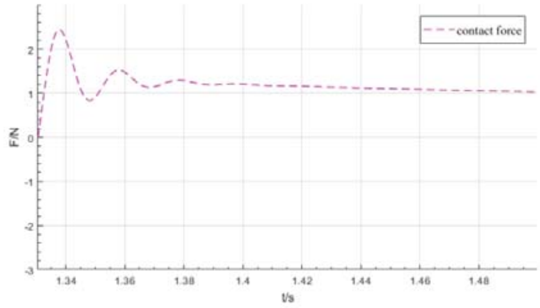

Fig. 7. Contact force of the actual sampling

For another trajectory track problem, the second simulation was designed. As Fig. 8 shown, the actual contact curve is divided into two parts, which represent the change of the trajectory caused by patients. After the correction, we can get the tracking force from different condition, see Fig. 9. F1 and F2 was defined respectively as the force along the initial curve and the "Doctor curve". And the figure shows that F3 along modified curve is kept around 1.5 N which meets the tracking requirements of force.

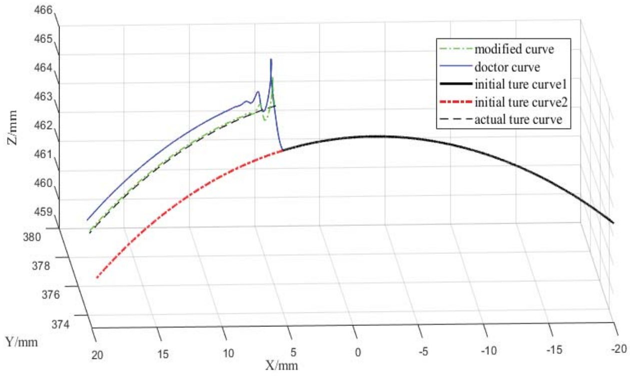

Fig. 8. Simulation curves of the modified process

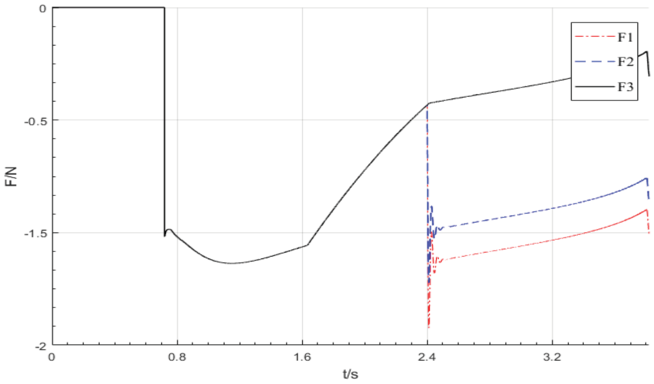

Fig. 9. Contact forces of the three cases

CONCLUSION

In order to reduce the workload of medical staff, reduce the risk of infection, and improve the operation accuracy, this paper proposed a remote human-robot collaborated strategy based on the pharyngeal swab acquisition robot. The experience of medical staff was integrated into the human-robot collaboration process, and the track was modified online. Finally, simulation results show the effectiveness of the proposed method. There are also some issues that need to be addressed in the future. In the contact process, in order to simplify the simulation, only the force in the depth direction is considered, while the force in the X and Z directions is ignored. In the future, impedance control analysis of contact forces from different angles is planned.

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