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Study on Motion Following with Feedback Force Disturbance in Interventional Surgical Robot System

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***Abstract*—Neurological intervention surgery (NIS) is surgery branch vascular interventional surgery, one kind of the minimally invasive. And it has become the mainstream of the treatment in the cerebrovascular disease. Robotic surgery system with the functions of haptic feedback and the doctor-patient separation has enormous significance for the development of NIS. However, in previous studies, the haptic feedback greatly affected the motion detection accuracy. This paper presents a novel interventional surgical robot systems. The aim is improving the accuracy of motion control while providing haptic feedback. This researches take the design thought of master-slave system which realized the function of doctor-patient separation. The slave side includes a novel guide wire resistance measurement structure and guide wire manipulator. The master side can provide haptic feedback for doctors and collect guide wire control commands from doctors. In this paper, design of the developed interventional surgical robot system was presented. And design experiments to assess the follow of axial movement, rotation. The feasibility of the developed system is proved.**

Index Terms —Interventional surgical robot system, Haptic feedback, Remotely control

I. INTRODUCTION

The neurological intervention surgery (NIS) is cerebral vascular interventional surgery. It is a kind of the minimally invasive surgery branch. And it has become the mainstream of the treatment in the cerebrovascular disease. Compared to the conventional craniotomy, the NIS has some advantages, like small wounds and fast recovery. During surgical operation， doctors rely on the haptic feedback of the hands and the medical images provided by the X-ray imaging device to operate the guide wire. However, exposed to the state of X-ray in a long-term will induce the serious health hazard for doctors. Hence, robotic surgery system with the functions of haptic feedback and the doctor-patient separation has great significance for the development of NIS [1]-[3]. Collision between the catheter and the blood vessel wall is the main source of danger. The collision force will not damage the blood vessels are an important condition for safe operation. However, the contact force between the catheter and the blood vessels that cannot be detected, it is not a warning directly to the doctor. The doctor can only operate at the end of the catheter. So it is necessary to use a variety of medical imaging (mainly for X ray imaging) to help guide their operation. Therefore, during operation the X-ray imaging was used. Irradiation for doctors and patients a long time can cause physical damage. Especially for doctors, after treatment for many patients, he will be a much higher proportion of the X-ray exposure time. Although doctors wearing protective clothing. It is hard to effectively protect the doctor's face and hands which radiation X-rays. Lead protective clothing has great weight, resulting in the doctor's stamina big challenge. When the fatigue, the doctor will be hard to ensure the quality of surgery. Long-term weight -bearing caused immense harm to the doctor's body especially the spine. To overcome these challenges, we need better technology and mechanisms to help and train doctors. Therefore, interventional surgical robot system came into being requested.

In recent years, most researches take the design thought of master-slave system. Those systems realized the function of doctor-patient separation. The doctors are liberated from the exposure to X-rays in the surgical environment, allowing for remote surgical operation. Master side is controlled by doctors. The main function is to provide a simulated surgical procedure for doctors and collect guide wire control commands from doctors. And the slave side is the guide wire operation, will be responsible for the control of guide wire in the patient’s intravascular [4]-[6].

But the existing surgical robot system is not adequate to replace conventional surgery. Not only because the machine is not as flexible as hands of human being but also the robot system cannot provide accurate haptic feedback to give the doctor operation guide.

However, these studies did not achieve the function of impeccable haptic feedback [4]-[5]. There exist two main problems during the process of haptic feedback. First, the haptic feedback mechanism should be integrated in the doctor-controlling side of the robotic surgical system, while the existing doctor-controlling side is difficult to collect control commands and provide haptic feedback to the doctor at the same time. More importantly, the feedback force of haptic feedback greatly affected the motion detection accuracy. It will directly impact on the precision of the interventional operation.

However, accurate demand is very high for the interventional procedures due to the surgical instruments inside the vessel when operating and any tiny mistake can be detrimental to the patient. A qualified surgeon needs to complete the operation within 1mm error, which stresses the importance of the accuracy of motion control in the interventional operation [6]-[12]. To address these challenges, this paper presents a new type of motion capture

mechanism. The method can accomplish function of force feedback and precise motion data acquisition at the same time. Use laser ranges finder to detect the axial displacement. Use of the code wheel to detect rotation. Crank-slider structure and reverse drive motor to provide force feedback [9]-[13].

In this article, a complete system was described, and using the experiment to verify the accuracy of motion detection which interfered by the feedback force. The rest of the paper is organized as follows. The developed interventional surgical robot systems were proposed. In the next section, method of motion detection and avoid interfered by feedback force were introduced. Then, experiments to measure the follow of axial movement, rotation. Finally is the conclusion part.

II. The Framework of System

The research adopts the design idea of the master-slave system. This system possess function of doctor-patient separation, allow remote operation. And it will liberation the doctor from the exposure operation environment in X-ray, operation diagram as Fig 1. The doctors are liberated from the exposure to X-ray in the surgical environment, allowing for remote surgical operation. Master side is controlled by doctors. Its main function is to provide a simulated surgical procedure for doctors and collect guide wire control commands from doctors. And the slave side is the guide wire operation, will be responsible for the control of guide wire in the patient's intravascular.

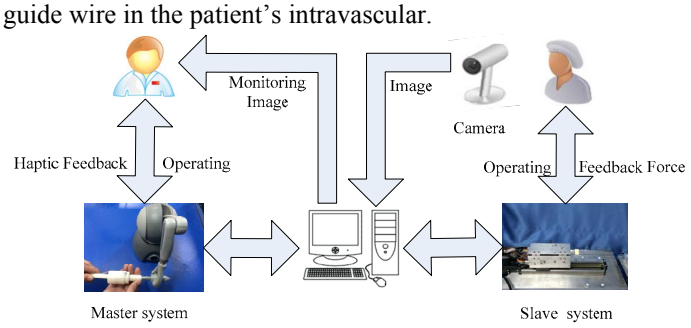

Fig. 1 Interventional surgical robot system

In the endovascular intervention operation, surgeon only needs two manipulations on catheter, rotation and insert. Therefore, there are two basic motions of the catheter, rotation, and go forward and backward. Fig. 2 shows the surgeon's actions during inserting motion [14]-[15].

In a real operation procedure, surgeon inserts the catheter to the lesion based on the hand's feeling. For example, the surgeon rotates the catheter when he/she feels more resistance from the catheter. Sometime the surgeon operates the catheter based on the DSA image but most of the time the surgery carries out the operation based on the hand feeling [15]-[17]. Haptic is the essential element for surgeons to finish operations.

A. The guide wire manipulator

The guide wire manipulator will imitate movements of physician's hand to operate the guide wire, the structure as showed in Fig 3. The green line in the figure represents the guide wire, the part A is a platform which fixed catheter sheath.

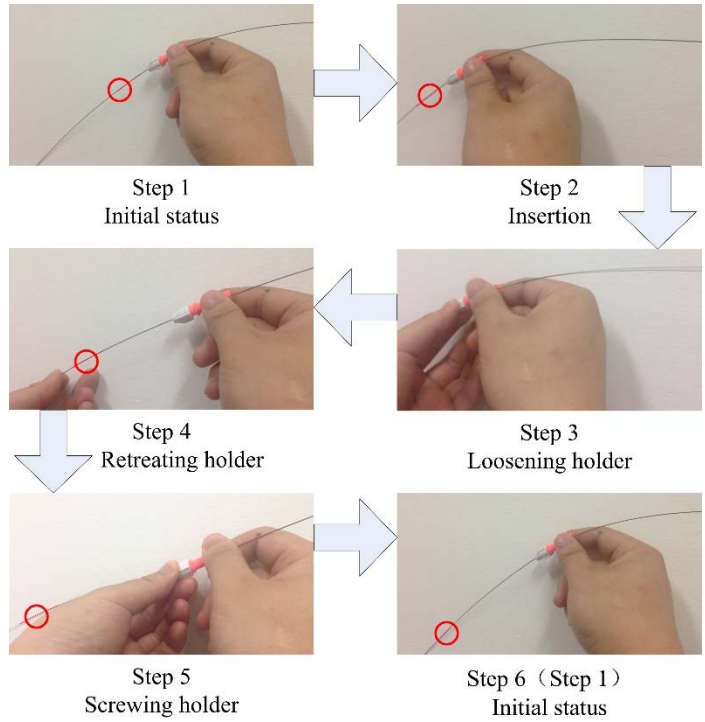

Fig. 2 Insertion process of the guide wire

It will contact with patients. Part B is guide wire manipulator. Its function is to control the guide wire rotary and fixed. It will be fixed in the part C. The part C is a slide motor. Its function is to drive the B part to the translation.

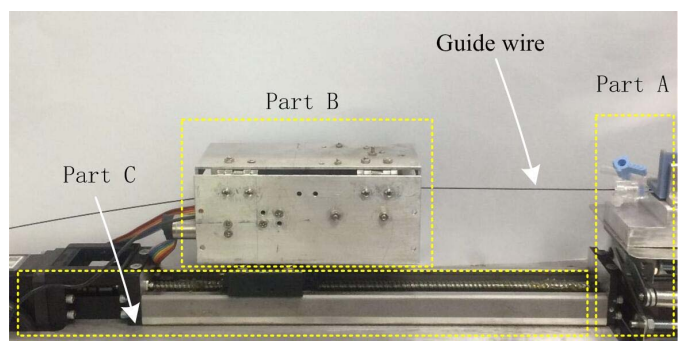

Fig. 3 The Guide Wire Manipulator

Part B is the mechanism which direct operation the guide wire. It is the core of the guide wire manipulator. Prototype of part B as showed Fig 4.

Element 5 is guide wire torque used in traditional intervention, uses it operating guide wire can effectively fasten the guide wire to prevent slipping, and increase the torque when the guide wire rotating. Using slider motor (part C) below the part B, guide wire manipulator can insert a guide wire. And using wheel gear (element 2). The guide wire could be rotated. Yellow equipment (element 7) is force sensor, it can detect weak resistance on guide wire, its precision can reach 0.001N.

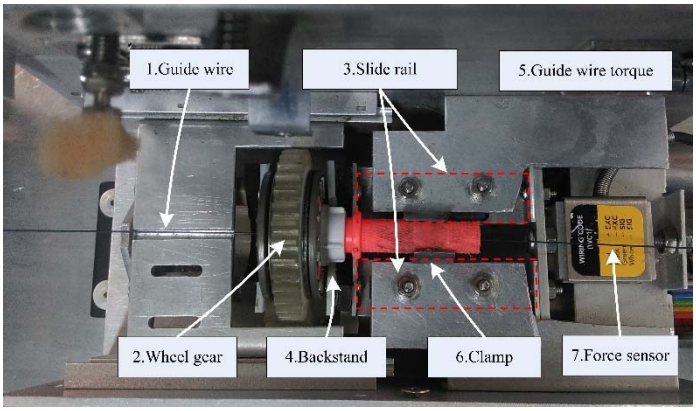

Fig. 4 Prototype of the Guide Wire manipulator

The wheel gear is fixed on the guide wire torque, and contact with the link. Another side of link contacts with the force sensor. When the clamp was loosened, the axial movement of the manipulator can drive the axial movement of the guide wire. During movement, resistance of guide wire will be passed on to the guide wire torque. Through the link, the resistance will pass to the force sensor. Because the link contacts with the slide rail, the frictional force is extremely small. This mechanism can guarantee the measuring accuracy. When the clamp was loosened, rotation of wheel gear can drive rotation of the guide wire. When the clamp is gripped the guide wire torque, rotation of wheel gear lets guide wire torque loosen guide wire. When the guide wire torque loosens, the axial movement and rotation of the manipulator can be controlled without affecting the guide wire.

In this system, using two MAXON DC motor control wheel gears and clamp, used for control guide wire torque rotating and stationary. Translation is achieved by one slide motor connected in the bottom of the equipment.

B. The surgeon's console

Master side is controlled by doctors, the main function is to provide a simulated surgical procedure for doctors, collect guide wire control commands from doctors, and provides haptic feedback to the doctor according to the resistance measured the guide wire. The equipment adopts the Phantom provides the resistance to the doctors [28].

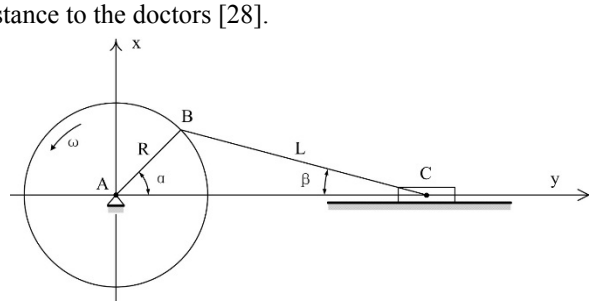

Fig. 5 surgeon's console based on structure of crank slider

The accurate demand is very high for the interventional procedures due to the surgical instruments inside the vessel when operating and any tiny mistake can cause injury to the patient, which highlights the importance of the accuracy of the feedback force in the haptic feedback function. Using the matrix analysis to establish the kinematics model of the crank-slide structure, analysed the interference of motion detection caused by the slider crank mechanism.

Show in Fig 5, a motor with an angle sensor is installed at the A point, the crank AB length is R, connecting rod BC length is L, the slider placed in the position of C. The A bit is set to the coordinate origin, theory travel of slider H is 2R, is in the range of [L-R, L+R]. In the doctor's control with simulated C slider guide wire, change through the A point in the motor angle sensor crank angle α, then using the kinematics model can obtain the accurate displacement of C point. At the same time, the implementation process of mechanical feedback is the use of motor provides a rotating angular velocity ω crank drives the sliding block C to the opposite direction of doctor operation exercise, so as to provide resistance F which is required for haptic feedback. In the slider crank mechanism, size of feedback resistance F can be obtained by variable kinematic model for crank angle α and angular velocity ω calculation. Through mathematical analysis to model the slider position C in crank slider mechanism can be defined:

$$\begin{pmatrix} x_c \\ y_c \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha & R(\cos\alpha - \cos\beta) \\ \sin\alpha & \cos\alpha & R(\sin\alpha - \sin\beta) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} R + L \\ 0 \\ 1 \end{pmatrix} \tag{1}$$

In this design, the use of crank slider mechanism, the slider C along the X axis motion, which is always y_c=0. When the sliding block and the guide wire quality simulation is m, can get the reverse driving force feedback mechanism provides F formula:

$$F = ma = mR\omega^2\left(\frac{\cos(\alpha+\beta)}{\cos\beta} + \frac{R\cos^2\alpha}{L\cos^3\beta}\right),$$
$$\beta = \arcsin\left(-\frac{R}{L}\sin\alpha\right) \tag{2}$$

One independent output motion parameters: the output force F of slider is indicated as:

$U=[u_1]^T=F$

Two independent input motion parameters: angle α and angular velocity ω of the angle of crank are indicated as:

$V=[v_1\ v_2]^T = [\ \alpha\ \omega\ ]^T$

Two independent dimension parameters: the length R of crank and the length L of linkage are indicated as:

$W=[w_1\ w_2]^T = [\ R\ \ L\ ]^T$

As for the doctor control site of robotic surgery system is based on crank-slider, the motor rotation error Δω and the measuring error of angle sensor are dominant errors of provide mechanical feedback function.

$$\Delta U = \left[\frac{\partial G}{\partial U^T}\right]^{-1}\left[\frac{\partial G}{\partial V^T}\Delta V\right] = \left[\frac{\partial G}{\partial U^T}\right]^{-1}\left[\frac{\partial G}{\partial v_1}\Delta v_1 \quad \frac{\partial G}{\partial v_2}\Delta v_2\right]$$
$$= \left[\frac{\partial G}{\partial U^T}\right]^{-1}\left[\frac{\partial G}{\partial \alpha}\Delta\alpha \quad \frac{\partial G}{\partial \omega}\Delta\omega\right] = \frac{\partial G}{\partial \alpha}\Delta\alpha + \frac{\partial G}{\partial \omega}\Delta\omega \tag{3}$$

Based on the calculating rules of random variables, mean $u_{|\Delta U|}$ be indicated as:

$$u_{|\Delta U|} = \frac{\partial G}{\partial \alpha}u_{\Delta\alpha} + \frac{\partial G}{\partial \omega}u_{\Delta\omega} \tag{4}$$

In the actual design, the length of the crank Land connecting

rod length R are selected as 200mm, the speed error used by the motor rotation is 0.4 rad / s, the angle sensor error is 0.001 rad. The mass m of the guide wire and the slider are both 160 g. The maximum allowed error is 0.03 N, the maximum offset error is 0.015 N. The actual output error of the mechanism is manifested by the equation (4), calculation result of $u_{|\Delta U|}$ is showed below. Reliability probability of the mechanism is showed below right.

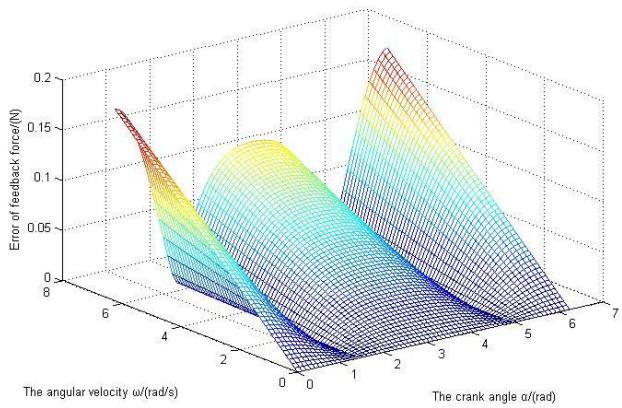

Fig. 6. Error of slider-crank mechanism

As can be seen from the chart Fig 6, the error a of feedback force change cyclically with the crank angle α changing, it also increases with the angular velocity. When the crank angle $\alpha = \pi / 2 + n\pi$, the error of the mechanism is minimum with the maximum reliability. When the crank angle $\alpha = 2n\pi$, the error of the mechanism is maximum with the minimum reliability. Therefore, the motion scope of the mechanism should be controlled in the vicinity of $\pi / 2 + n\pi$ as far as possible of position to reduce the error of the system.

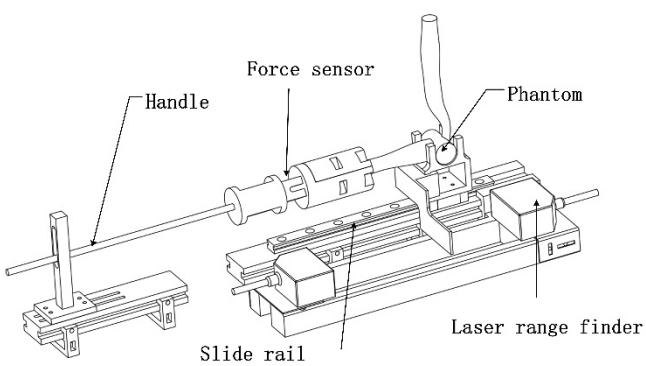

Fig. 7 The structure of the master side

However, those errors will reduce the accuracy of motion detection. This study will develop a novel mechanism, which can obtain precise motion information when the feedback force provided. The structure of the master side is shown in Fig 7. The function of slide rail is to ensure the axial movement of the handle is not affected by friction. Force sensors are used to detect haptic feedback on the fingers of a doctor. Using the force measured by the sensor, closed-loop control of haptic function can be achieved. The haptic feedback function will be optimized. The laser range finder is used to measure the axial direction of the handle. The role of the handle is to replace the guide wire to accept the doctor's operation.

According to this idea, the prototype of the master side was developed. The prototype of the master side is shown in Fig.8.

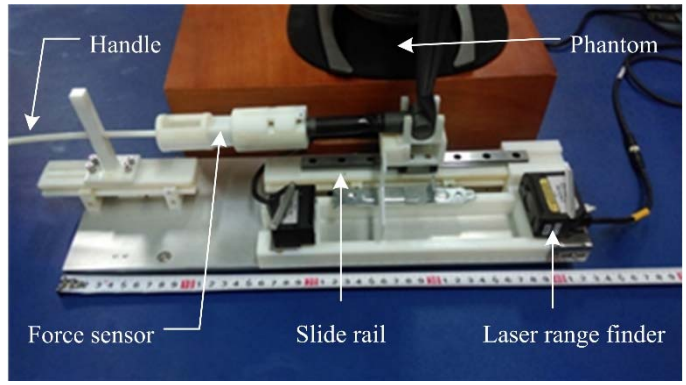

Fig. 8 The prototype of the master side

III. Experiments

An insertion experiment was carried out to evaluate the effect of the interventional surgical robot system. Fig. 9 shows the mechanism for catheter insertion in the proposed system. Basically, the process is same as cardiac catheterization intervention. The users were asked to move the catheter, endovascular evaluator (EVE) as treatment object, was used to detect operation process of the volunteers, shown in Fig. 9.

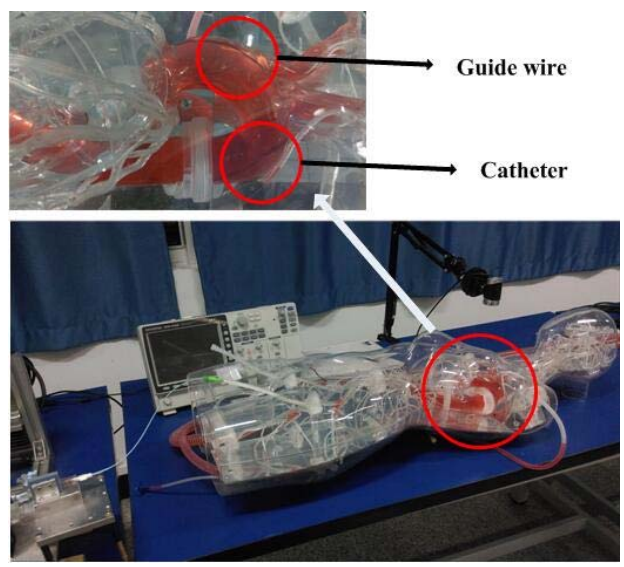

Fig. 8 Medical training vessel model

The translational and rotational positions were recorded, as shown in Fig 10 and Fig 11. As a result, we achieved conventional catheter movement including axial push-pull motions with range from -30 ~ 30 mm and the twisting motion ranging from 0 ~ 250°. The maximum error of axial movement is 0.76mm. And the maximum error of rotation is 2.4 degree.

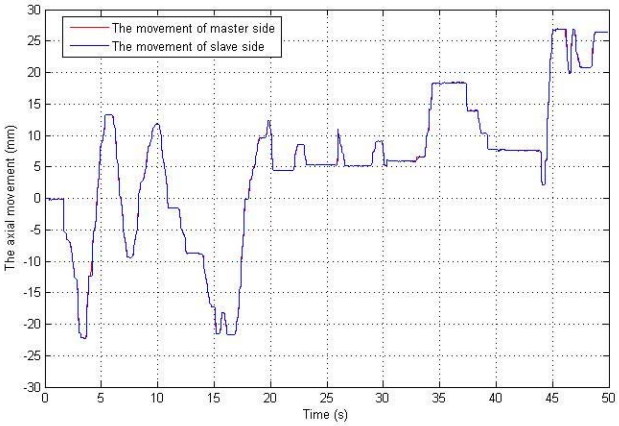

Fig. 10 Follow of axial movement

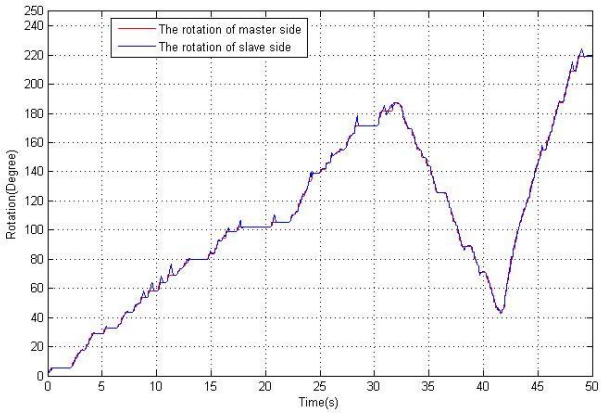

Fig. 11 Follow of rotation

IV. CONCLUSIONS

This paper introduces a new type of intervention operation robot system. This system simulates hand motion of doctors to operate on the guide wire. The doctor can cast the clinical operation skill fine. The slave side includes a novel guide wire resistance measurement structure and guide wire manipulator. The master side can provide haptic feedback for doctors and collect guide wire control commands from doctors. Accurate motion information can be obtained when the system is disturbed by a feedback force. And design experiments to measure the follow of axial movement, rotation and force. The feasibility of the developed system is proved. In the future, the research group will maintain the same action principle, the structure is improved into a more compact, precise and closed design, to meet the needs of the clinical operation is required for stable, health requirements.

ACKNOWLEDGMENT

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