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A New Robot Architecture for Tele-Echography

Adriana Vilchis, Jocelyne Troccaz, Philippe Cinquin, Kohji Masuda,
and Franck Pellissier

***Abstract*—This paper presents a slave robot carrying an ultrasound probe for remote echographic examination. This robot is integrated in a master-slave system called robotic tele-echography (TER). The system allows an expert operator to perform a remote diagnosis from echographic data he acquires on a patient located in a distant place. The originality of this robot lies in its architecture: the cable-driven robot is lightweight and semirigid, and it is positioned on the patient body. In this paper, we describe the clinical application, the system architecture, the second implementation of the robot, and experiments performed with this prototype.**

***Index Terms*—Medical robotics, nonrigid robot, tele-echography.**

I. INTRODUCTION

Among many types of medical equipment, ultrasound (US) diagnostic systems are widely used because of their convenience and innocuity. Performing US examination involves good hand-eye coordination and the ability to integrate the acquired information over time and space; the physician has to be able to mentally build three-dimensional (3-D) information from both the two-dimensional (2-D) echographic images and the gesture information and to make a diagnosis from this information. Specialized physicians with these skills may be lacking in some healthcare centers or in emergency situations. Teleconsultation is, therefore, an interesting alternative to conventional care. Development of a high-performance remote diagnostic system, which enables an expert operator at the hospital to examine a patient at home, in an emergency vehicle, or in a remote clinic may have a very significant clinical added value.

In this domain, existing works can be structured in two subdomains: works exclusively related to the telemedicine aspect, mainly image transmission and manipulation (see, for instance, LOGINAT [1] and TeleinVivo [2]), and works integrating robotic assistance to the expert operator. A subclass of systems allows automating an echographic examination using a robot (see [3]–[5]). Finally, a second category of robot-based systems enables the remote examination of patients by a distant expert with [6], [7] or without [4], [8], [9] force feedback. Many of the robot-based systems integrate conventional robot architectures. However, medical robots belong to safety-critical systems. In such systems, the robot shares its working area with operators (medical staff) and has a close interaction with the patient. For echographic examinations, the robot is in contact with the body of the patient and imparts forces to it. Therefore, one major technical objective of this research was to propose a new architecture of low-weight, compliant, safe, and portable medical robots. The robotic tele-echography (TER)[1] system described in this paper belongs to the category of robotic-based systems with force feedback and includes a robot with an original kinematic architecture.

As can be seen, several systems are being developed worldwide to provide remote echographic examinations. None of them has yet been proven to answer this problem in a superior way to its competitors. [4] and [5] must be highlighted since they present a large range of control schemes enabling shared control, force control, visual servoing, and teleoperation. The main originality of TER lies in its robot architecture. As in [4], [5], [8], and [9], one objective was to design a light robot. The slave robot in Masuda's system is also lying on the patient's body and is the most similar to ours,[2] but differs in several ways: its user interface integrates two joysticks requiring teleoperating the robot in a decoupled way, it has no force feedback, and its robot is rigid. As compared with [7] which includes force feedback, one advantage of TER is that its slave robot architecture is more generic. For TER and Mitsuishi's systems, the haptic device is more sophisticated than strictly required by the application; this will be discussed later.

The main focus of this paper is the slave robot. Two prototypes were designed, realized, and experimented upon. The first prototype was based on pneumatic actuation with McKibben muscles and a slightly different kinematic architecture. Based on experimental work, we decided to modify the robot. The second prototype is described in this paper. We invite the interested reader to refer to cited papers for more details on the first prototype [10], force rendering [11], or telecommunication protocols [12]. The paper is organized as follows. Section II is devoted to the general presentation of the TER system, its general architecture, and operating mode. The clinical application constraints and the tele-echography protocol are described. Sections II–VI describe the slave robot. Section III focuses on the slave robot mechanical architec-

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[1] TER is a French acronym for robotic tele-echography.

[2] Those rather close robot mechanical designs were performed in parallel, each group independently of the other.

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Fig. 1. Master site. (left) Elements of the master site. (right) Graphical user interface of the master site.

ture. The kinematic model is provided in Section IV. Section V presents the experimental results concerning both the robot performance and the system behavior. Section VI is dedicated to conclusions and perspectives.

II. OVERVIEW OF THE TER SYSTEM

A. Description of the TER System

The teleoperated TER system allows the expert physician to move a virtual probe in a manual, natural, and unconstrained way and safely reproduces this motion on the distant site where the patient is examined by means of a slave robot holding the real probe. The virtual probe is placed on a haptic device on the master site, as shown in Fig. 1 where one can see the graphic user interface. The haptic device in the master site is used to give the operator a realistic perception of the normal force between the echographic probe and the patient's body [13]. It is based on a PHANToM device (from SensAble Technologies Inc.) which has six degrees of freedom (DOFs) and renders 3-D force information. The PHANToM allows position and orientation tracking of the virtual probe within a workspace of $16 \times 13 \times 13\,\mathrm{cm}^2$ with a maximum force of 6.4 N. The haptic device is aimed at preserving medical expert proprioception and gesture feelings which are necessary to synchronize the ultrasound images with the probe motion.

The slave robot moves the real echographic probe as specified by the distant expert. The obtained US image is continuously sent from the slave site to the expert that has to perform the examination and provide a diagnosis. The ultrasound data is a one-way real-time data flow. The system uses a Matrox Meteor board and FFMPEG library, which provides a large choice of video codec such as MJPEG, MPEG1, MPEG2, MPEG4. The nominal image size used is 640×480 pixels with 8 b encoded, but at low bitrate, the size is divided.

Force information is sent from the slave site to the master site. Because the Phantom requires a 1-kHz loop, a local model at the master site is also used to compute force information between two force acquisitions transmitted from the slave site. A generic mesh is deformed to the patient shape and mechanical properties attached to the mesh triangles allow for realistic force computation.

A nonexpert operator is located close to the patient and supervises the procedure so that he can interrupt it in any case of emergency. The patient, the operator, and the expert can communicate during the examination. Fig. 2 gives a data flow diagram corresponding to a remote echography with TER. Three successive stages allow initialization, remote examination, and session closing.

Trajectory motions performed by the virtual probe are converted to a sequence of points. Points are sent every 10 ms. When received by the slave site, these points are converted into joint values for the slave robot (see Section IV). Different types of networks are considered: ISDN (typically, 2 or 3 128 kb/s connections are sufficient), LAN, and VTHD (about 1 GB/s). The basic idea is to adapt the TER system to different types of clinical applications, users, and healthcare infrastructures.

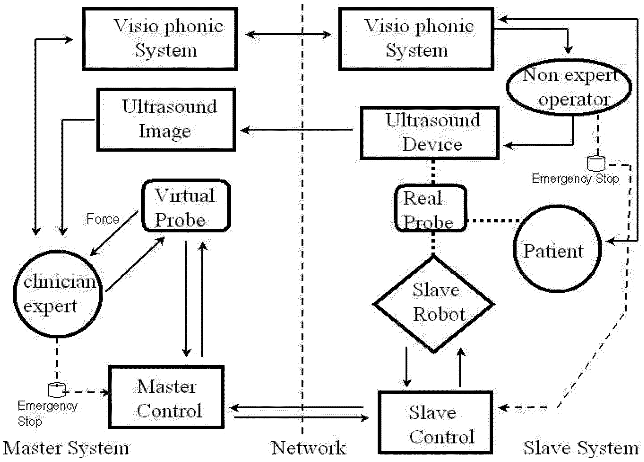

Fig. 2. Data flow in the TER system.

B. Analysis of the Echographic Probe Motions

In a first stage of the project, we analyzed typical echographic examinations in order to design the TER operating protocol and to specify the slave robot motion. To determine the motion and force range of the remote echography system, the executed motions and applied forces of a real echographic probe were analyzed while a physician was examining a patient under a conventional procedure. Even though TER is generic in its principles, we focused on abdominal examinations and, in particular, on follow-up of pregnant women.

The observed motion and gesture zones were used to define the working surface. In the examinations of pregnant women, the working surface obviously depends on the stage of pregnancy. As the pregnancy evolves, the working surface becomes larger and rounder. The system was designed such that its workspace was compatible with an examination of a pregnant woman at any stage of her pregnancy.

Predefined shapes are used to approximate this surface: a plane for very early pregnancy or spheres of different sizes for later stages. A more complex but more precise approach consists in deforming a predefined surface mesh representing the patient from data acquired on the patient by remote palpation. The selected work surface is used for kinematic model computation, in particular, for the determination of the robot orientation relative to the body of the patient in the translation motion.

In order to guarantee a correct US image acquisition, the condition of contact of the echographic probe with the body surface must be satisfied at each instant. This requires the application of suitable forces. The measurements of the effort variation on the abdomen during a real examination were performed using a dynamometer. We can consider three ranges of pressures: minimum pressures from 0.6 to 0.8 dN, standard pressures from 0.8 to 1.2 dN, and maximum pressures from 1.2 to 1.5 dN. These measurements determine a range of authorized efforts, which have to be considered for remote examination.

III. SLAVE ROBOT DESIGN

The robot architecture proposed in this paper is quite different from classical ones and from most robots used in previous works. Its principles have been patented.

The slave robot has a double structure decoupling probe translation movements from probe rotation and pressure ones. It is a cable-driven nonrigid structure evolving on the patient body surface.

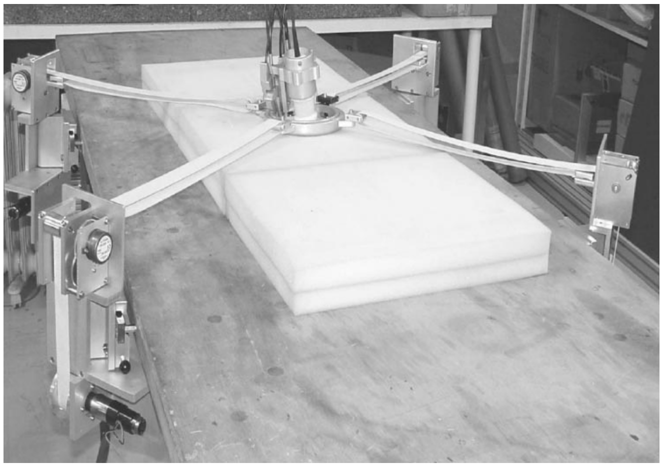

Fig. 3. Robot general view.

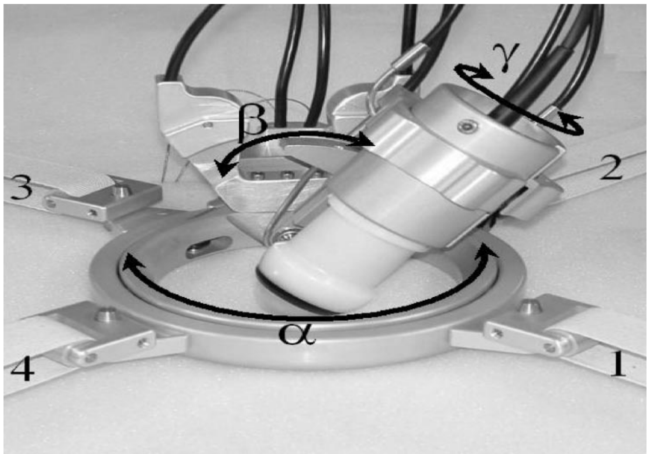

Fig. 4. Robot architecture (closeup on the orientation ring).

One structure is parallel (see Fig. 3) and the other one is serial (Fig. 4). The first parallel structure enables the translation motion of the US probe on the body surface. This structure is mounted on the consultation bed at four independent fixation points (see Fig. 3). The translation movements are controlled by four direct current (dc) motors connected by straps to a wrist carrying the probe, also called orientation structure. The wrist is a serial structure having four DOF: three for the probe orientation and one for fine translation along the probe axis (Fig. 4). These DOF are also connected to dc motors by cables. Both groups of actuators can be controlled simultaneously.

The workspace of the translation structure depends both on the bed on which it is installed and on the surface on which the robot has to move. The largest workspace is in the horizontal plane containing the straps extremities. In the current setup, it corresponds to a 50 × 50 cm square. For a different setup on a larger bed, the workspace could be slightly enlarged. The maximum length of each strap is about 80 cm; when used on a smaller surface, the straps are kept extended, thanks to the mechanical design. This workspace is modified when the robot is placed on a rounder surface.

The wrist workspace is the following: the rotation ranges are, respectively, ±90°, ±40°, ±90° for α, β, and γ. The translation range of the probe along its axis is 2 cm.

Potentiometers have been chosen as joint position sensors. They are associated with the cable lengths and angular values of the robot. A force sensor (constraint gauge) is included on the slave robot for force feedback to the haptic device.

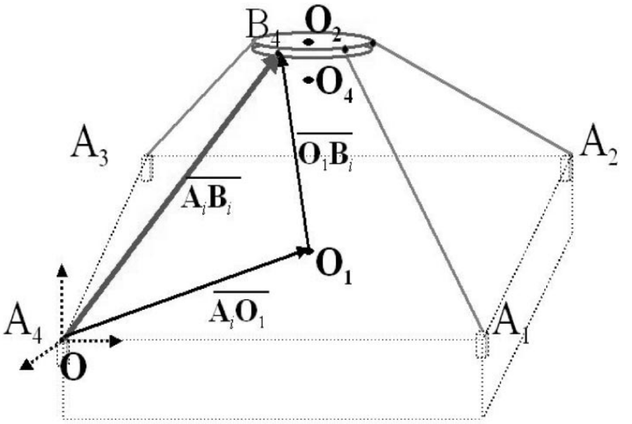

Fig. 5. Absolute reference frame and kinematics for the translation structure.

IV. Kinematic Model

The posture information which comes from the master site is $(x, y, z, \alpha, \beta, \gamma)$, where $x, y,$ and z define the position of the probe and α, β, γ are the Euler angles with a ZYX convention. The angles for the orientation structure are in a ZYZ Euler convention, we compute these angles from ZYX representation.

In the system reported here, the use of a nonrigid structure using cables and the motion on a free-form surface (plane, sphere, or free-form surface adapted to the patient) make the kinematic problems more complex than it is for rigid and serial robots. We use an approximation of the surface as introduced in Section II.

To compute the joint coordinates (the strap lengths) from the posture information provided by the master site, we define different frames (see Fig. 5).

- *Inertial system (FX)*
- *Absolute reference frame (REF)*: (point $\mathbf{O_1}$) The origin of the system is located on the barycenter of $\mathbf{A_i}$ $(i = 1, \ldots, 4)$ points corresponding to the attachment of the straps.
- *System translation frame (ST):* (point $\mathbf{O_2}$) The origin of the system is placed at the center of the translation ring.
- *System end-effector (OT):* (point $\mathbf{0_4}$) The origin of the system is placed at the end of the ultrasound probe. It corresponds to the theoretical contact point between the probe and the skin of the patient.

As shown in Fig. 5, the points $\mathbf{A_i}$ (reference points for length computation) and the points $\mathbf{B_i}$ (attachment to the wrist) are defined as the extremities of the straps. The wrist position is defined by (1). The strap length is approximated by (2).

$$\begin{aligned} {}^{\mathrm{REF}}\overrightarrow{A_iB_i} ={}& {}^{\mathrm{REF}}\overrightarrow{A_iO_{\mathrm{REF}}} + \mathrm{REF}\left(\overrightarrow{O_{\mathrm{REF}}O_{\mathrm{OT}}}\right) \\ & + R_T{}^{\mathrm{OT}}\left(\overrightarrow{O_{\mathrm{OT}}O_{\mathrm{ST}}} + \overrightarrow{O_{\mathrm{ST}}B_i}\right) \end{aligned} \tag{1}$$

$$L_{AB_i} = \left\| {}^{\mathrm{REF}}\overrightarrow{A_iB_i} \right\| \tag{2}$$

where R_T represents the rotation matrix connecting OT to REF, defined for a spherical work surface. Four variables are used to define the translation ring configuration (two of them defining its position over

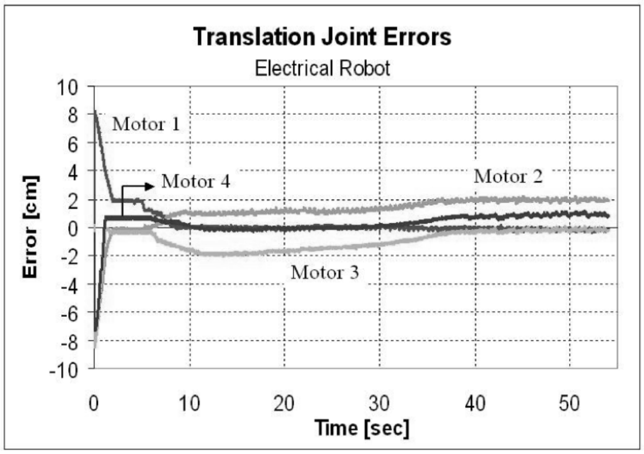

Fig. 6. Translation joint errors during circular tracking.

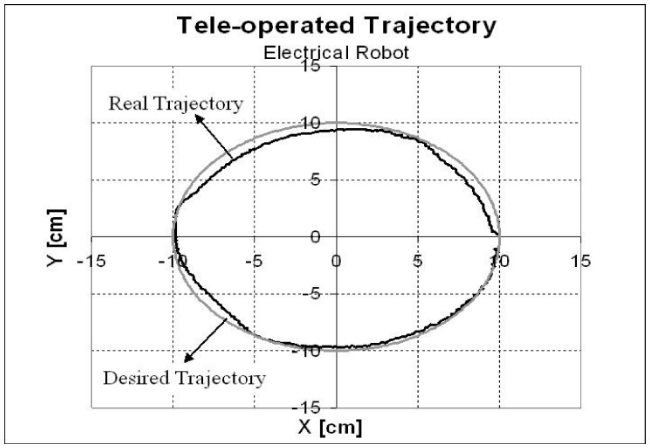

Fig. 7. Circular trajectory tracking error.

the curved surface and two defining its orientation). In this way, this ring displaces tangentially to the defined surface.

V. EXPERIMENTAL RESULTS

A. Performance of the Slave Robot

An external open-loop position control integrating an internal closed-loop control on joint values was implemented and tested. The cable or strap lengths are turned to volts joint values to be sent to the electrical motors using calibration data, thanks to calibration functions.

Fig. 6 shows the joint errors for the translation structure corresponding to one quarter (top-right quadrant of the circumference made during the tracking task shown in Fig. 7).

The robot repeatability is 4 mm. Its resolution on the working surface is 2 mm for the main translation and 1° for the orientation. The resolution on the axis of the probe is 1 mm. The precision is about 10 mm. Those numbers have to be analyzed keeping in mind several facts: first, the echographic plane is not a mathematical plane but a "pseudo-plane" which has a volumic shape. We can approximate it by a parallelepiped although its thickness varies depending on the distance to probe surface. With typical probes for abdominal exams, its thickness is 2 or 3 mm at the focusing distance, larger close to and far from the probe surface. Concerning lateral motions in the "pseudo-plane," since the probe is generally several centimeters large, the resolution limit is not critical. The objective is not to reach a given absolute location but to explore an anatomical environment with continuous image feedback. This objective is made possible. The normal force in the US probe direction (Z axis) varies from 3 dN (contact established) to 27 dN.

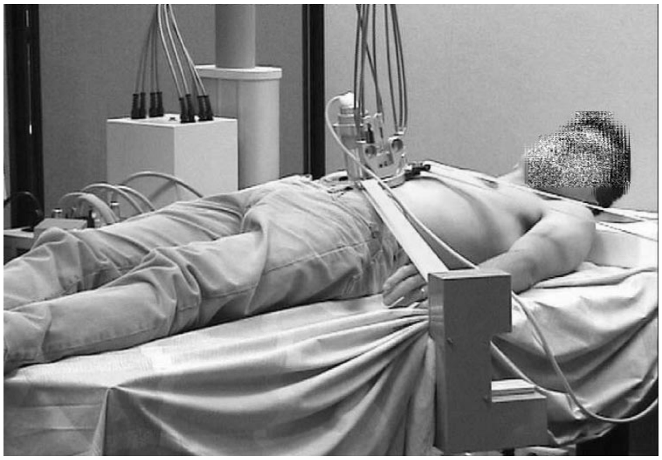

Fig. 8. *In-vivo* experiment (Toulouse-Grenoble, France). Slave robot moving on the volunteer's body.

B. Teleoperation Experiments

The first series of experiments were performed with the first prototype on phantoms and a volunteer. In order to describe the system performance from the end-user (physician) point of view, each of the clinicians participating in these tests had to complete a questionnaire. The global evaluation of the system by the end users was good. These experiments demonstrated that the use of the TER system is very intuitive; there is a short adaptation time of 5 to 10 minutes necessary for the medical expert to feel comfortable with moving the virtual probe using the haptic device. The quality of images and robot controllability were considered as good by the physicians. The medical experts were able to recognize internal structures of the echographic phantom and to follow them. During the *in-vivo* experiment, the physician was able to localize and explore liver anatomical structures.

The position errors of the slave robot appeared to be of limited importance for the medical expert since he controls the probe motion as a function of what he sees in the echographic image rather than as a function of the position of the real probe relative to the body surface. However, the first system suffered from significant drawbacks, which led to the design described in this paper. Firstly, the muscle reaction time was rather low and the muscle mechanical robustness was limited, leading to frequent replacements and long calibration phases which are not compatible with a clinical use. Moreover, the nonrigid orientation structure had limited mechanical stability and led to a rather poor controllability of the probe orientation.

The second version of the system was integrated in September 2002. It was first tested with a LAN network in our laboratory, then with a ISDN connection between the TIMC laboratory and France Telecom R&D Company (about 10 km distant). In October 2002, a first series of experiments using ISDN 256 kb/s between Toulouse and Grenoble (600 km) (see Fig. 8) took place with the following caracteristics: MPEG4 image format at 120 Kb/s (about 4 images/s), H323 QCIF visioconference at 64 kb/s, and less than 64 b/s for the bidirectional haptic data flow. It was successfully performed both with a fetal phantom and with a volunteer by three physicians from the domains of gynecology and emergency care. In December 2002, another demonstration of the system was made at the Telemedicine Congress of the French Army Health Department in Toulon (300 km from Grenoble) with a ISDN 512 kb/s with: MPEG4 image format at 320 kb/s, H323-QCIF visioconference at 128 kb/s (haptic flow remained unchanged). In Toulon, physicians from the Army using the system successfully performed abdominal examinations of a volunteer located in Grenoble. They appreciated the ease of use of the system and good moving performance of the slave robot. The volunteer did not report any discomfort (in particular, no excessive probe pressure on the abdomen) arising from the use of the robot.

The clinical validation of this prototype started in June 2003 in the context of a French national project. The clinical protocol is ready and has been validated by the ethical committee as the Huriet French law requires. VTHD connections between Brest and Grenoble hospitals (1125 km) are used for the remote echographic examination of patients with abdominal aortic aneurysms (AAA). The evaluation, involving 100 patients, will be based on both quantitative and qualitative criteria.

VI. Discussion and Conclusion

An original slave robot was described and preliminary experiments with the TER system were presented. The system enables a medical expert to perform in real time, via several types of communication links, an echographic examination on a patient remotely located. The first *in-vitro* and *in-vivo* experiments performed with the TER system are very promising.

There have been relatively few efforts to produce special-purpose robot designs for medical robots whilst such an approach generally results in systems best suited to the clinical application. Moreover, echography is not surgery: precision is not so much an issue and echography involves permanent contact of the tool with the body of the patient during the robot displacements. One approach, exemplified by the UBC system [4], [5], used parallel linkages and backdrivable actuators to manipulate the ultrasound probe. The advantages of this system include the use of several control modes, among which are impedance control and visual servoing on anatomical structures. Drawbacks include a relative bulkiness and the absence of force feedback for teleoperation in the current version. The main advantages of our system are the ability to adapt, by design, to the body shape of the patient without any special control scheme, and the light weight and compactness of the robot. Clinical validation should demonstrate the ease of use in a clinical environment. The absolute system accuracy is limited, but we think that tele-echography does not require high precision, and this could be improved if an application requires by integrating a localizer on the slave site and adding a Cartesian closed loop in the control scheme. Adding force control would also be very useful to guarantee contact conditions. Our setup could be simplified because the haptic device is not adapted to the application. We are developing a 1-D force feedback virtual probe that would replace the Phantom.

The TER system was developed having in mind as a first stage the remote echographic examination of pregnant women, but the system is generic and can be applied to any abdominal echographic diagnosis. It will be validated for AAA pathologies. Its application to other anatomical sites, such as carotid artery or lower limb examinations, would require the adaptation of the slave robot architecture to a new working area. However, the general working principles will remain the same for these new applications.

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