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**Yara SEEG: Introducing the Platform for Robotic
Assisted Epilepsy Neurosurgery**

São Carlos

2023

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Monografia apresentada ao Curso de Engenharia Mecatrônica, da Escola de Engenharia de São Carlos da Universidade de São Paulo, como parte dos requisitos para obtenção do título de Engenheiro Mecatrônico.

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**São Carlos
2023**

ACKNOWLEDGEMENTS

ABSTRACT

Silvestre, G.S. Yara SEEG: Introducing the Platform for Robotic Assisted Epilepsy Neurosurgery. 2023. ??p. Monograph (Conclusion Course Paper) - University of São Paulo, São Carlos, 2023.

This research introduces a novel concept for a robotic system, Yara, specifically designed for Stereoelectroencephalography (SEEG) neurosurgery. The platform integrates collaborative robotic assistance, leveraging the precision of robotic systems, and is adaptable to various surgical environments. The study evaluates the system's final accuracy by replicating a SEEG neurosurgery procedure on a 3D reconstructed patient. The patient's head, cranium, and brain models were reproduced using different materials derived from tomography. The surgical procedure was simulated, starting from planning, proceeding through fiducial registration, and culminating with electrode placement. A post-operative tomography was performed to compute the error between the planned electrode trajectories and the final position of each entry and target point, providing a comprehensive assessment of the system's accuracy and effectiveness in SEEG neurosurgery.

Keywords:

RESUMO

Silvestre, G.S. **Yara SEEG: Introducing the Platform for Robotic Assisted Epilepsy Neurosurgery.** 2023. ??p. Monografia (Trabalho de Conclusão de Curso) - University of São Paulo, São Carlos, 2023.

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

SEEG - Stereoencephalography

ROS - Robot Operating System

CONTENTS

1 INTRODUCTION

At the end of the 20th century, there was a fundamental transformation in the methods used to perform surgical procedures. For many interventions, the invasive nature has been considerably reduced, bringing superior results such as a better survival rate, lower incidence of complications, and faster recovery in terms of functional health and quality of life. This emphasis on less invasive approaches, also known as minimally invasive surgery (MIS), has been gaining momentum and has been the subject of intensive research and development of new surgical techniques in recent years (??).

In 1985 there was the first interaction between medicine and robotics with the *PUMATM* manipulator focused on brain biopsies. Surgical interventions expanded their horizons with the *da VinciTM* robot, enabling tasks to be carried out with precision and strength beyond human capacity and allowing surgeons to perform tasks impossible to perform without robots (??).

The Da Vinci[®] Surgical System has had a positive impact on surgery. Other examples include the Renaissance[®] System. The MAKO has been shown to increase the accuracy rate, and provides precision and eliminates the need for hand instruments in orthopedic procedures. Showing that robotic systems have contributed to significant improvements in the results of surgical operations, reducing trauma for patients, and accelerating postoperative recovery (??).

This work focuses on the development of a robotic system for the treatment of epilepsy through SEEG surgery. Robots such as ROSA, Neuromate and Circ are capable of carrying out such treatment. However, each of them has its disadvantage. To better understand the context of this development, it is necessary to understand the characteristics of epilepsy (Section ??), the types of crises and their impact on the patient's life, as well as the existing treatment methods (Section ??).

1.1 Epilepsy

Epilepsy is a chronic brain disease characterized by a long-lasting predisposition to generate seizures, not caused by any immediate insult to the central nervous system, and by the neurobiological, cognitive, psychological, and social consequences of recurrences of seizures (??). This is the most common neurological disease worldwide, affecting different social classes, races, ages, and geographic locations (??).

The definition of *epileptic seizures* is: repeated and transient episodes that manifest themselves through patterned behaviors, mirroring the underlying neural processes associated with the condition (??). Although all people with epilepsy experience seizures, not

all individuals with seizures have epilepsy. Epileptic seizures can also occur after an acute injury to the central nervous system (CNS) of structural, systemic, toxic or metabolic origin. These events are considered acute manifestations of the insult and may not occur when the underlying cause has been removed or the acute phase has passed (??).

Epileptic seizures are categorized according to three main characteristics: origin in the brain, state of consciousness during the seizure and level of body movement. Seizures can be classified as focal or generalized based on the first characteristic. The second characteristic considers whether consciousness is intact or impaired during the seizure, while the third characteristic refers to body movement, which may present motor or non-motor reactions (??).

Motor seizures encompass a variety of distinct manifestations. Atonic crises are characterized by a sudden and temporary loss of muscle tone, resulting in a sudden fall of the individual. On the other hand, tonic crises involve a sudden and prolonged increase in muscle tone, leading to intense stiffness. Clonic seizures are marked by rhythmic and repetitive muscle contractions, which can affect different parts of the body, while myoclonic seizures are characterized by rapid and sudden muscle contractions that can involve a specific muscle group or the entire body. Epileptic spasms, automatisms and hyperkinetic seizures are also categorized (??).

On the other hand, non-motor crises can present different forms of manifestation. They can be autonomic, involving dysfunctions in the autonomic nervous system, such as changes in blood pressure or heart rate. In addition, there may be crises of behavioral arrest, during which the individual may appear paralyzed or unable to perform voluntary movements. Cognitive crises affect cognitive function and may include memory lapses or mental confusion. Emotional crises are related to changes in the emotional state, such as feelings of fear, anxiety or euphoria. Finally, sensory crises affect the senses and can cause abnormal sensations, such as visual or auditory hallucinations (??).

1.2 Treatment methods

Among patients with epilepsy, approximately 30% experience drug-resistant seizures, representing a significant portion of the global population, estimated at 70 million people. In such cases, resective surgery appears as a viable therapeutic option. This procedure is considered in patients with disabling focal epilepsy who are unresponsive to drug treatment and whose seizures originate in a specific region of the brain that can be removed with minimal risk of neurological or cognitive dysfunction (??). Resective surgery offers the possibility of significantly improving the quality of life of these patients, providing adequate control of seizures and reducing dependence on high-cost and potentially harmful antiepileptic medications.

Correctly locating the focus of seizures is a crucial aspect in preparing for resective surgery in patients with epilepsy (??). Localization methods are applied to accurately determine the focal region, aiming to minimize the invasiveness of the surgery while seeking complete removal of the area of focus to cease seizures. Accuracy in locating the focus has a significant impact on the effectiveness of the surgical procedure, as it can help avoid undesirable consequences associated with the resection of unaffected areas. This is especially important, as the removal of critical areas of the brain can result in functional deficits, such as impairment of speech, memory, motor coordination, among other functions, depending on the location of the focus. Therefore, ensuring accurate location of the focus is essential to guarantee good surgical results and minimize potential adverse effects.

1.2.1 Non-invasive video-EEG

Scalp EEG aims to investigate the cause of seizures in a non-invasive method. This procedure involves placing electrodes on the patient's scalp, using a cap or similar support, for monitoring in the interictal (between seizures), ictal (during seizures) and post-ictal (after seizures) periods. This configuration, with electrodes mounted superficially to the head, allows the measurement of the difference in electrical potential on the scalp caused by the electrical activity of neurons located mainly close to the skull. 32, 64 or 96 electrodes are placed across the entire surface of the scalp, each electrode corresponding to a channel. Systems with 256 channels are also adopted for more refined analyzes that require more channels per area (??). In summary, monitoring of seizure using scalp EEG as a preliminary analysis for diagnosis and location of the seizure is essential before proceeding to invasive methods (??).

1.2.2 Invasive EEG: Subdural EEG (SDE) and Stereoencefalography (SEEG)

A method developed to increase the ability to measure brain activity in relation to scalp EEG was Subdural EEG (SDE) or electrocorticography (ECoG). In this method, a part of the skull is removed, and an electrode array is placed in direct contact with the brain, on the surface of the cortex (Figure ??). This method allows for the acquisition of signals with less noise and greater amplification compared to (??) scalp EEG. The electrodes will remain on the patient for a few days to collect data in ictal and interictal periods. However, the electrode array placement procedure is an invasive method that presents a high frequency of postoperative infections, mainly caused by materials not sanitized during surgery. Furthermore, EDS requires two craniotomies (removal of part of the skull) to access the brain to place the electrodes and remove the electrodes (??).

In France, in the 1950s, Jean Tilarach and Jean Bancaud developed a method that aims to monitor deep parts of the cortex through the insertion of deep electrodes seeking to replace the SDE (??). This method was called Stereoelectroencephalography (SEEG) and today it is one of the most adopted invasive methods for locating the focal

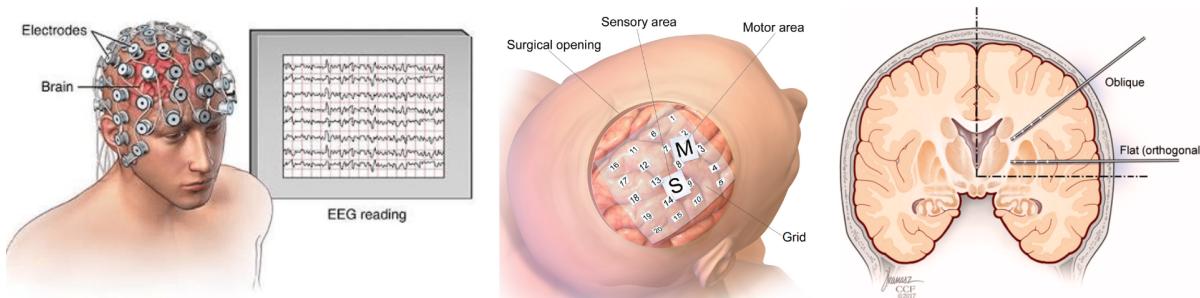


Figure 1 – Positioning of electrodes in scalp electroencephalography, electrocorticography and stereoelectroencephalography procedures respectively (??) (??) (??).

zone of seizures. SEEG does not present many of the problems presented by SDE. In this method, cylindrical electrodes (more like small wires) are introduced through small holes in the skull, without the need for craniotomy. SEEG has lower rates of infection, hemorrhage, neurological deficits and morbidity compared to SDE, in addition to being a faster procedure, allowing the analysis of deeper brain tissues and having shown greater effectiveness in localizing and controlling seizures after surgery. treatment (??). Figure ?? illustrates the positioning of electrodes in scalp EEG, Subdural EEG (electrocorticography) and SEEG.

Electrodes implanted by SEEG must be precisely placed for proper identification of the epileptogenic zone (EZ) (??). Planning prior to surgery is carried out to define the number of electrodes, the position of the entry points and the target point of each electrode. Metrics are defined for evaluating the effectiveness of SEEG operations, constituting a basis for evaluating different SEEG methods. Entry points are defined as the point at which the electrode initiates contact with the surface of the brain. Target points are defined as the final position of the electrode, usually in a region within the brain. Widely adopted metrics are the Euclidean distance between the planned entry points and the post-surgical entry points, the distance between the planned target points and the post-surgical target points, and the angle between the two vectors formed by the planned and post-surgical target entry points representing the orientation error.

1.3 Stereoelectronencephalography: operation methods

SEEG operation techniques began with Tilarach using x-ray images for planning and checking electrode positioning. Since the inception of SEEG, the development of mechanical stereotaxic apparatus that fixes the skull and guides electrode placement has been the focus to achieve the best precision during surgery. The first apparatus was called the Tilarach apparatus and featured pins for fixing the skull, support for the x-ray tube and radiographic film (??). Popular devices today date their creation to the same time, such as the Leksell in Sweden. With the advent of computed tomography, surgeries began to be planned based on slices, allowing a three-dimensional understanding of the areas of investigation. Devices that use the three-dimensionality of tomography images were adapted, adding a support with a diagonal cut in the shape of an N, allowing the calculation of the height of each tomography slice in relation to the device coordinates. This system became known as *N-Localizer* and is widely used in current neurosurgeries (??).

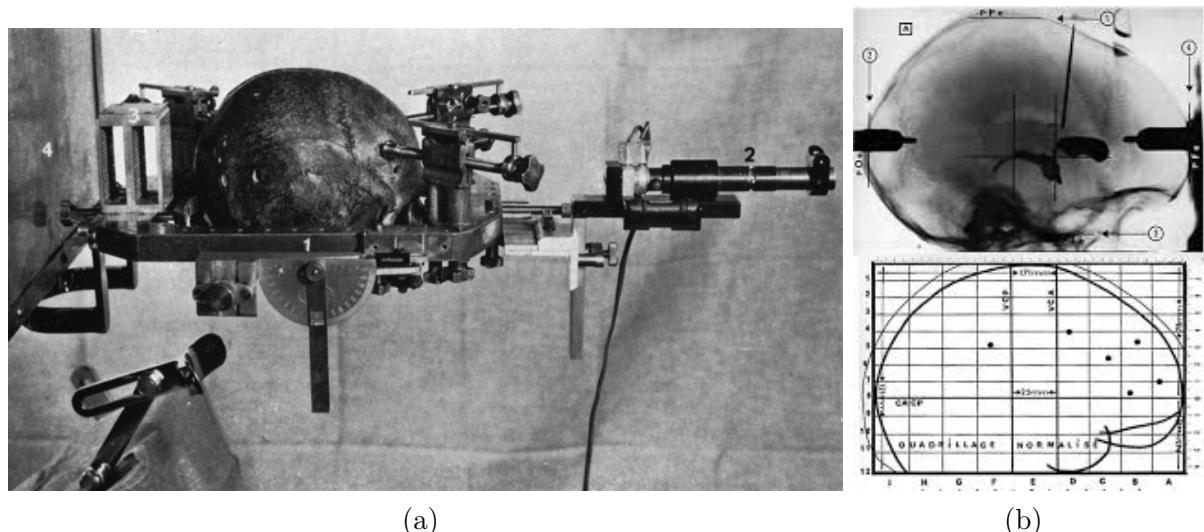


Figure 2 – (a) presents Tailarach’s *frame* with x-ray supports and (b) presents an example x-ray image alongside the coordinate system developed by Tailarach (??).

1.3.1 Frame-based surgeries

The original SEEG technique consisted of introducing parallel electrodes, at least, to an orthogonal sagittal or coronal view using the Cartesian map called Tailarach coordinates (??). Subsequently, variations of the technique were explored with the introduction of stereotaxic arcs that can be fixed to devices such as the Leksell or CRW and that allow the introduction of oblique electrodes. Therefore, the assessment of the impact on precision between different techniques for implanting oblique or orthogonal electrodes was studied in (??). Figure ?? presents the Leksell G apparatus and the N-Localizer.

Originally, the calculation of the coordinates of each electrode in relation to the apparatus was carried out manually, using the *N-Localizer* geometry. Software for surgical planning was developed so that the calculation of the coordinates of the entry and target points was automated using image processing methods containing the N-Localizer (??). These software also feature crucial planning tools, such as fusing standard CT images, contrast-enhanced CT images for angiography, and MRI-generated images.



Figure 3 – Frame Leksell G without N-Localizer and with N-Localizer respectively (??).

Image fusion allows better planning, allowing the analysis of the vascularization of regions close to the electrodes, as well as allowing the analysis of the physiology of the region to be investigated. In general, a CT image is fused with MRI for electrode trajectory planning. During surgery, the stereotaxic apparatus (Leksell, CRW) is fixed to the patient's head and the N-Localizer is fixed to the apparatus, to allow calculating the coordinates of each electrode in relation to the apparatus. The patient is taken for another tomography with the apparatus fixed and the volume generated is merged again with the pre-surgical CT and MRI. This allows the software to process the images, find the intersection of the N-Localizer rods in each slice containing an electrode, and calculate the *entry* and *target* Cartesian coordinates for using the stereotaxic ruler, or spherical coordinates for use of the stereotaxic arch.

We can cite as examples of planning software Brainlab Elements (??), Renishaw Neuroinspire (??) and Mevis MNPS (??). In addition to software that allows the calculation of the coordinates of each electrode for the use of stereotactic devices such as the ruler for positioning orthogonal electrodes or the stereotaxic arc for oblique introduction, neuronavigation software has been developed. In these systems, cameras are used to track a guide, allowing the surgeon to visualize the positioning of the tool during surgery. Neuronavigators are widely used in procedures for biopsies and removal of brain tumors.

However, most neuronavigation systems present themselves as a manual tool in which the surgeon has access to the position and orientation of this tool in relation to the patient's head. For SEEG surgery, the lack of a support that allows this tool to be fixed in a fixed position becomes a difficulty in applying these systems in this type of surgery. In

this regard, Medtronic, with the Stealth Autoguide (??), developed a system that allows the tool to be fixed, facilitating the drilling of the skull and the fixation of the guide screw.

Surgeries based on stereotactic devices have a broad history of use, but they also have disadvantages in relation to more recent systems, such as robotic systems. Among the disadvantages, the stereotactic *frames* operation requires the placement of the apparatus at the beginning of the surgery, the performance of a tomography with the N-Localizer and the fusion of this volume with the CT and MRI images taken (generally days before surgery) used for planning. This process is necessary for the planning software to calculate the coordinates of each input point and target in relation to the frame. This process is not necessary with the use of robotic systems in surgeries called *frameless*, in which a stereotactic apparatus is not used.

The Table ?? presents a comparison between the procedures necessary to perform *frame-based* surgery compared to *frameless* surgeries. The greater number of steps during surgery increases the time needed to perform the surgery and may result in loss of accuracy due to non-deterministic procedures, possible human errors. Analyzing the Leksell apparatus as an example, the placement process must be carried out in such a way that the *frame* plane is aligned with the plane formed by the Anterior Commissure and Posterior Commissure by at least degrees. This process is generally performed manually so that the alignment is not deterministically measured, and may eventually exceed the acceptable limit of a few degrees of deviation.

The second problem related to the *frame-based* surgery procedure is the need to perform a tomography with the device immediately after its placement. The logistics of this process would be ideal if the CT scanner was available in the same operating room where the patient is undergoing the procedure. However, it is utopian for hospitals to have one CT scanner per operating room. Some hospitals have some operating rooms with CT scanners, but the scalability of this process and the availability of these rooms given the competition from other parallel surgeries underway in the hospital make logistics complex. The most commonly used solution is to transport the patient to the CT scanner, increasing surgery time and possibly causing unwanted movements of the apparatus due to external factors during transport (such as vibration, knocks and contacts) after the CT scan and, therefore, compromising the final accuracy. of surgery.

After tomography with the device, the fusion of CT images generated with the device with pre-surgical images are also sources of errors. In more detail, image fusion consists of aligning two volumes (set of slices generated in CT) so that they both represent the same physical structure. This is necessary because the volume resulting from the CT scanner depends on factors such as the patient's position and the coordinate system intrinsic to the CT. The alignment of two CTs, in the case of SEEG surgery, allows the planning performed with the preoperative CT to be aligned with the CT performed with

Table 1 – Comparison between frame-based and *frameless* procedures for SEEG.

Surgery based on stereotactic apparatus.
1. CT, MRI and preliminary surgery exams.
2. Orthogonal trajectory planning based on preliminary evidence before surgery.
3. Start of surgery and fixation of the head in the stereotaxic apparatus (Leksell).
4. Tomography with Leksell and <i>N-Localizer</i>
5. Fusion of CT, MRI and CT images with Leksell to calculate the coordinates of each electrode in relation to the apparatus
6. Using the stereotaxic ruler, drill the skin and skull using a 3 mm drill with an appropriate end point.
7. Fixing the guide screw to the skull
8. Using the guide screw, insert the temporary stylet into the intracranial space to the target point for electrode guidance.
9. Remove the temporary stylet and, through the guide screw, insert the depth electrode into the intracranial space to the predefined destination.
10. Screw the electrode cover onto the guide screw.
11. Repeat steps 6 to 10 for the remaining electrodes.
Robot-assisted surgery
1. CT, MRI and preliminary surgery exams.
2. Planning orthogonal trajectories based on preliminary evidence before surgery using the robot's neuronavigator.
3. Facial registration using fiducial points of the face
4. Positioning the robot and drilling the skin and skull using a 3 mm drill with an appropriate limit stroke.
5. Fixing the guide screw to the skull
6. Using the guide screw, insert the temporary stylet into the intracranial space to the target point for electrode guidance.
7. Remove the temporary stylet and, through the guide screw, insert the depth electrode into the intracranial space to the predefined destination.
8. Screw the electrode cover onto the guide screw.
9. Repeat steps 4 to 8 for the remaining electrodes.

the stereotaxic apparatus. In this way, the result of the fusion is the planning of the surgery, containing entry and target points in the same reference as the apparatus images, thus allowing the calculation of the coordinates necessary to align the ruler or stereotaxic arc in each trajectory.

However, the alignment of CT images presents an error caused by the method used for alignment. Alignment algorithms can use the intensities of each *pixel* for the best alignment, as well as manually selected fiducial points to minimize the fusion error. Even in the most ideal case, this process is not perfect and will contribute to the final error of each trajectory. In short, fixing the device, transporting it to the CT scanner and fusion of images are some of the sources of errors during surgeries based on stereotactic devices.



Figure 4 – Competing robots capable of performing SEEG surgeries: Zimmer Biomet ROSA ONE Brain, Brainlab Cirq and Renishaw Neuromate respectively.

1.3.2 Robot-based surgeries

The literature presents developments of *frameless* systems for SEEG surgeries focused on facilitating surgical procedures, increasing the precision and safety of surgery (??) (??). The pioneering robot introduced to the market capable of performing SEEG neurosurgery was Renishaw's Neuromate in 1998 (??). Figure ?? presents the system, featuring a triangular base and a Mayfield or Leksell support for fixing the skull. Another system developed by Medtech in France and acquired by Zimmer Biomet was ROSA ONE Brain, also capable of performing SEEG surgeries. Later, Brainlab also developed Cirq for use in surgeries such as SEEG. It is worth mentioning that the three systems are compatible, in addition to SEEG, with brain biopsy surgeries and DBS (widely used in the treatment of Parkinson's).

Neuromate was the first neurosurgery robot to be commercially developed, but it also presents challenges in its application (??). The biggest challenge is the need for an exclusive operating room for the robot, due to the inability to move the system. This makes the hospital's logistics difficult and makes purchasing it impossible due to this restriction. Furthermore, one of the biggest difficulties with Neuromate is the need for a dedicated operating room for the robot, without the possibility of moving it between operating rooms. Moreover, Neuromate has only 5 degrees of freedom (DOF), constituting an under-actuated robotic system, losing mobility and positioning capacity in relation to conventional robotic systems (with 6 DOF).

The Cirq robotic system is used as a neuronavigation tool. A device with reflective

spheres is fixed to the robot's flange, similar to that used in common neuronavigators. This device is viewed by an infrared stereo camera and the position of the tool is calculated. Each joint of the robot has only brakes and, therefore, is not actuated, but allows the system to remain static during procedures.

Its adjustment is done semi-automatically, where the surgeon approaches the robot to the desired position and the robot adjusts itself with an actuator fixed to its flange. The neuronavigator is used to operate this system, which has: a camera carriage; a screen carriage; and a robotic manipulator fixed to the operating table. Combined with other devices present in the operating room, these three devices bring difficulties in logistics and in organizing the space in the room compared to systems that have only one carriage. Finally, the cost of the complete system is comparatively higher than that of competitors on the market.

ROSA ONE Brain, even though it doesn't have the disadvantages present in other systems, has its own problems. The system, unlike Cirq, for example, is not collaborative. In other words, even though it is designed to perform a task together with the surgeon, ROSA does not feature sensors that are present in collaborative systems, such as measuring joint torque, collision detection, and automatic braking when an emergency is activated. This aspect makes ROSA a conventional robot applied to collaborative tasks, putting doctor and patient safety at risk. Yara, the system proposed in this project, uses collaborative systems, validated worldwide for tasks that involve joint operations with humans, ensuring the surgeon's safety.

ROSA is not collaborative, constituting an industrial system that has limited capacity to understand the surrounding environment, putting patient and doctor safety at risk. Conventional, non-collaborative industrial robots must be isolated from humans at a safe distance in their workspace for most workplace safety regulations in the world. This concept has not been applied to surgical robots as they are not under industrial legislation. In the literature, the use of collaborative systems for neurosurgery within commercial systems was not identified. KUKA was a pioneer in the development of collaborative systems approved by international regulations for medical applications with the KUKA LBR Med. This increases safety in robotic manipulation during surgeries, unlike existing systems on the market.

The presence of robots for stereotactic surgeries in Brazil and developing countries is still timid at the moment. Figure ?? presents competing robots and their incidence in hospitals in Brazil. According to our investigation, there are no hospitals that have purchased ROSA or Neuromate in the country. Cirq was acquired by Hospital Moinho de Vento in Rio Grande do Sul in 2022, in addition to having performed some surgeries in other hospitals in the country. This represents a marketing opportunity, as entry into the Brazilian brand is difficult without technical support from the manufacturers of ROSA

and Neuromate in the country. With this, Yara aims to meet the demand for improving SEEG procedures in the country in the short term, in Latin American countries in the medium term and in other continents in the long term.

1.3.3 Mechatronic Systems and Planning Software

The Stealth AutoGuide - Medtronic (??) is not a robotic arm, but is defined as a robotic system coupled to the apparatus that fixes the patient's head (Mayfield, Leksell or CRW) and assists the surgeon in aligning the final trajectory of each electrode. Lastly, software that assists in planning the surgery by calculating the coordinates for the stereotactic apparatus also qualify as less sophisticated but more accessible competitors. Brainlab Elements is an example of a computer-assisted method that presents advanced functionalities and excellent usability. Renishaw's Neuroinspire is also a renowned cranial planning system. Mevis' MNPS is presented as a national solution for planning brain neurosurgeries. However, all of these software programs are dependent on the stereotactic apparatus and the difficulties pointed out in Section ??.

1.4 Introducing Yara

Yara presents itself as a robotic platform that is able to perform frameless procedures, reducing risks, surgery time and increasing precision in relation to frame-based procedures. A collaborative system, which maintains the surgeon's safety, while allowing better usability and manipulation of the robotic system. The system has software that allows surgery planning with the entry and target points of each desired electrode, the fusion of MRI and CT images, automated registration using depth cameras and collision-free movement of the robot for alignment to the desired trajectory. Furthermore, Yara also works as a neuronavigator, increasing the number of surgeries supported. The surgeon can move the robot with his hands, as in the neuronavigation process, and use the brakes to lock the desired position. In this way, Yara presents itself as an innovation in the field of stereotactic surgeries, surpassing the limits of state-of-the-art robotic systems.

The *Yara* system, proposed in this project, should begin applications for SEEG and should extend its capacity to biopsy and DBS surgeries once validated in humans this year. This initial step is mainly due to SEEG surgery having slightly more lenient requirements in terms of accuracy than DBS and biopsy. Completing the SEEG validation stage, tests will be carried out for DBS and biopsies for validation and, with this, our system is on par with competitors such as ROSA, Neuromate and Cirq in terms of supported surgeries.

2 DEVELOPMENT

2.1 Monitoring phase

All procedures begin with collecting patient data, including monitoring the manifestations of seizures and collecting medical images. This phase is essential for the diagnosis and understanding of the patient's symptoms, as well as the initial triage for the classification of seizure type. The patient history is listened to understand the past seizures symptoms. Data collection can start by imaging scan in inter-ictal periods using PET-CT. Video-EEG is a candidate for the better understanding of the seizure symptoms as well as the initial guess of the epileptogenic zone. SPECT scan can be performed during the ictal period to help the diagnosis.

During this monitoring phase, the patient can stay in the hospital for a couple of days until the diagnosis is completed, and a possible treatment is planned. In general, 70% of the patients get free from seizures by the medication prescription. However, the other group doesn't get the same result, falling into the drug-resistant group. In those situations, the surgical treatment is the most viable option and the invasive methods are considered, such as SEEG or ECoG. As discussed in Sec. ??, the SEEG method has benefits over the ECoG. Once SEEG method is selected, Yara robot can help the surgery starting from the electrode trajectory planning (a.k.a SEEG planning).

2.2 SEEG Planning phase

The Yara NeuroNav interface is prepared to SEEG planning. This interface was developed to address neurosurgeons and neurologist needs during the planning. The goal of the planning is to select target points that make the electrodes cross the most probable chance to be the epileptogenic zone. Entry points needs to be selected in a manner that the electrode trajectory is safe and follow a path without the collision with critical structures such arteries or eloquent regions of the brain. Typically, electrodes have between 5 and 15 contacts along the depth, spaced by A couple of millimeters. Between 5 and 10 electrodes are placed in the SEEG procedure.

To perform the plan, it is necessary to have a detailed visualization of the internal structures such as the brain, skull, and vascularization. Hence, CT and MR with and without contrast are performed. To allow a complete visualization in the same reference frame, a common approach is to perform the Image Fusion, aligned the scans to have the same reference frame. This alignment allows the overlap of the scans, improving the interpretation of the internal structures, consequently helping the SEEG plan for the safety and for a better decision on each electrode position.

2.2.1 Image Fusion

Yara NeuroNav applied an Image Fusion method presented on (??). The goal is to minimize metrics such as volume similarity, distance similarity to find the best transformation between one source image and one target image. Since scans are sequences of images, slices in each human body axis, the method is applied for each image to find a global transformation using specific optimization approaches. For human registration between CT-CT, CT-MRI and MRI-MRI, the method performed correctly after few parameters tuning with acceptable volume similarity. We focused on the visualization features, which allowed the user to run the method to overlap the scans, modify fusion parameters and the transparency accordingly.

2.2.2 Electrode placement

After the analysis of the images, electrodes can be planned by determining the entry and target points, the type of electrode containing basic information such as spacing, coordinates, number of contacts, and the dimensions of each electrode. This step is performed a couple of days before the surgery, the planned electrode is saved and loaded on the day of the surgery to the interface. Small adjustments can be performed during the surgery if needed.

2.3 Robot-Scan Registration phase

With the planning completed, and the surgical room equipped with our system integrated with the robot, it is necessary to perform a registration before starting the operation. This is because the interface and the robot do not share the same coordinate space. Therefore, it is necessary to align the two vector bases of the systems for the positions of the previously created markups to be passed to the collaborative robot. By definition, this practice is called registration, which is based on the idea of determining an operation that aims to transform points from one vector system to another system (??). In the application described in this article, intermodality registration was used, involving the alignment of coordinate systems from various acquisitions.

The procedure involves identifying multiple fixed points known as fiducial points in the interface, which are then correlated with points obtained from the patient using the robotic manipulator. When touching the target point with the tool developed by the team, the operator interacts with the robot's flange button located on the seventh joint of the manipulator. The interface points are then sent to the robot's control module, which applies the Iterative Closest Point (ICP) Algorithm. For this, the robot and the Yara system controller communicates via TCP network, with categories of messages and commands that share the necessary data.

Expanding on the ICP method by (??), the goal is to find the matrix \mathbf{R} and vector \mathbf{t} that best solves the Euclidean transformation ?? given a matched set of 3D points like $\mathbf{P} = \{\mathbf{p}_1, \dots, \mathbf{p}_n\}$ and $\mathbf{P}' = \{\mathbf{p}'_1, \dots, \mathbf{p}'_n\}$.

$$\forall i, \mathbf{p}_i = \mathbf{R}\mathbf{p}'_i + \mathbf{t} \quad (2.1)$$

The procedure is to select fiducial landmarks, distinguished points on the patient face, in the CT/MR and hand guide the robot in the physical space, with the correct order. The sets correspond to at least 3 points each, for example, the two temples and the nasion, and they're used to indicating the correlation between the two sets. A transformation ${}^{robot}T_{scan}$ is calculated that minimizes the reprojection error and best aligns the CT/MR space with the real scenario in the operating room.

The reprojection error is computed by transforming the fiducial points in the source space to the target space (robot space) and comparing with the collected fiducials in the target space (Equation ??).

$${}^{robot}P_{c proj} = {}^{robot}T_{scan} {}^{robot}P_{c scan} \quad (2.2)$$

$$Reproj = \| {}^{robot}P_{c robot} - {}^{robot}P_{c proj} \| \quad (2.3)$$

2.4 SEEG Operation phase

The next step is to place the electrodes in the patient. Continuous communication between the neuronavigator and the robot is essential, allowing the neurosurgeon to determine the sequence of each insertion. As previously mentioned, communication between the interface and the robot's control system occurs over a dedicated network. The control module utilizes ROS framework¹ to connect the subsystems, which is the manipulator controller (KUKA Sunrise) developed in Java. This integration uses the TCP/IP communication protocol provided by the robot's API (a feature not present in all robotic systems manipulators).

Moreover, the communication system enabled the development of advanced features for the neuronavigator, such as real-time transmission of the tool's position, transformed to the interface's coordinate system, control of the robot's joint positions, and the provision of the distance between the target point and the tool's starting point. These features significantly improve user visibility and procedural precision.

In the operating room, the operator must exercise great care, as it is a highly controlled environment where their actions can potentially harm the patient, other individuals, or equipment. Therefore, implementing safety logic is crucial to prevent any

¹ <http://wiki.ros.org/noetic>

unforeseen incidents. The Yara system presents a digital twin of the robot within the interface. This digital twin allow the clinicians to understand the robot space during the operation. Furthermore, each planned movement is presented and requested approval to continue. This is a fundamental procedure to perform each step of the surgical process with safety.

Yara system helps the surgeon on the drilling process by providing the precise depth of the drill that is safe, crossing just the skull bone and not reaching the brain tissue. After that, the surgeon places a drill guide that will guide and fix the electrode in the right direction. Finally, the interface shows the exact depth that the surgeon needs to introduce the electrode, to reach the desired region inside the brain.

2.5 Accuracy Evaluation

As discussed in Section ??, an SEEG method must be sufficiently accurate to place each electrode on the planned position and orientation. The accuracy can be measured by the Euclidean distance between the planned entry point and the entry point achieved after the surgery. The same method applies to the target point. The angle between the entry to target vector $\vec{P_{target}} - \vec{P_{entry}}$ for the planned electrodes and the post surgery electrodes reflects the orientation error. SOTA methods show that frame-based methods reach XX mm TODO

Yara can perform all the necessary steps for the surgery. This state was achieved through a partnership between the development team and frequent evaluations of the system with the neurosurgery group at HCFMRP-USP. To meet the accuracy requirements to perform SEEG surgeries, we measured the system's accuracy using two methods: 1: insertion of electrodes into a synthetic brain and 2: insertion of rods into a measuring template (*phantom*).

2.5.1 Accuracy assessment with synthetic brain



Figure 5 – Model with synthetic brain for performing simulated surgery and evaluating the system.

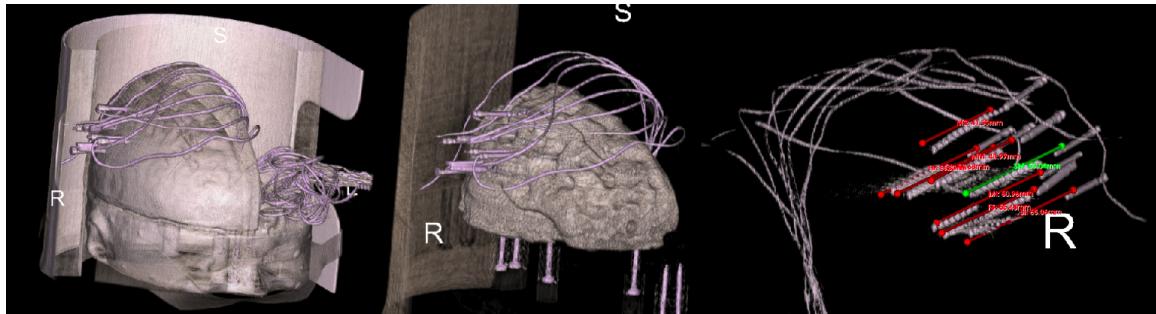


Figure 6 – Comparison between preoperative and postoperative images for evaluation of surgery and calculation of trajectory errors.

Tests with a synthetic brain were carried out by 3D printing the surface of a patient's head (in accordance with research use), together with a hemisphere of the brain produced with silicone material, aiming to imitate the consistency of the organ. This specific patient underwent SEEG surgery at HCFMRP using the Leksell (i.e., non-robotic surgery). Tomography and magnetic resonance images and the surgical planning used in the surgery were used to replicate the surgery using the robot. The procedure was carried out successfully with the insertion of nine electrodes.

After the operation, the model was taken to the tomography to acquire images that show the internal positioning of the electrodes. Through this, it was possible to compare the positioning of the inserted electrodes with the surgery planning, seeking to calculate the system error. As presented in Section ??, the error between the planned entry and target points and those achieved postoperatively are evaluation metrics for SEEG surgery and were calculated in this process. Figure ?? shows the synthetic model developed during the operation and performing the tomography. The comparison between the planned and achieved electrodes with the fusion of the postoperative CT with the preoperative images (Figure ??) allows the calculation of Euclidean distances between the planned and achieved trajectories and, therefore, allows the evaluation of the system's accuracy (Table ??).

The precision achieved in methods using the stereotaxic apparatus (Leksell, CRW) reported in (??) on average is 7.1 mm for the entry point and 8.5 mm for the target point. Therefore, the results acquired with robotic surgery with 1.30 mm input and 3.07 mm target meet expectations and are sufficient to perform SEEG surgery. To complement the evaluation, we carried out tests using a method that allows repetition in a simpler way, by using a target template to compare the planned target point and the one achieved (Figure ??). This system does not require the tomography stage and the manufacturing of synthetic brains, reducing the cost of each test and improving the logistics and speed of testing.

Electrode	1	2	3	4	5	6	7	Mean	Std.
Δ Entry (mm)	1.47	1.81	1.58	1.71	0.56	0.95	1.04	1.30	0.25
Δ Target(mm)	2.57	2.62	3.72	2.26	4.88	3.48	1.97	3.07	0.25

Table 2 – Error in positioning the entry and target points planned and reached after surgery using a synthetic brain model.

2.5.2 Accuracy assessment with SEEG *phantom*

To validate the accuracy of the system using *phantom*, the 3D printed surface of the patient's head was used and, instead of using a synthetic brain, a base containing cylinders with a conical top was produced. The tops of each cone were used as target points so that the system must reach them with a thin metal rod that represents the electrode. The planning stage is carried out so that the input points are arbitrary and distributed across the entire surface of the skull for greater variability, and the target points are points located on the peaks of the cones. The registration stage is carried out using fiducials on the surface of the patient's head (similar to validation with a synthetic brain). In the operation process, the robot positions itself at each electrode, the interface shows the length at which the drill limit switch must be positioned, and the hole is drilled. The length of the guide to the target point is calculated by the interface, and a rod of the correct length is inserted.

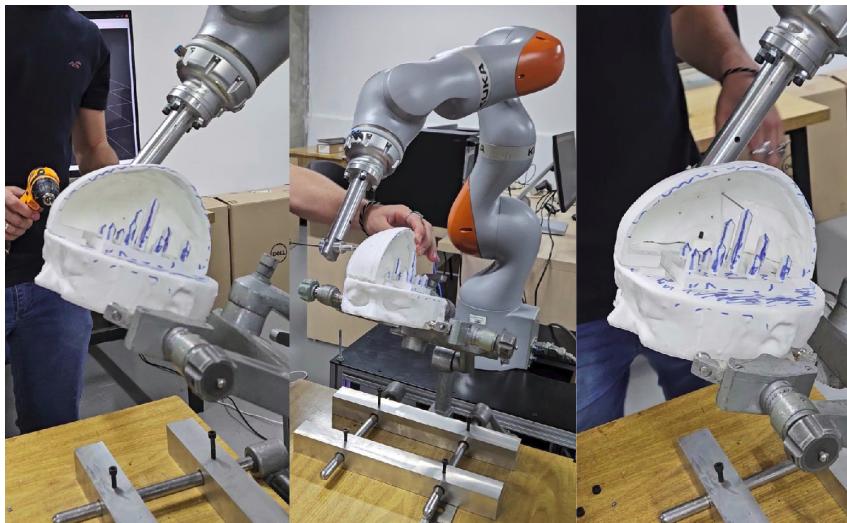


Figure 7 – *Phantom* produced with cylinders with a conical top for error measurement using a stereo camera.

To evaluate the positioning, a stereo camera was used, allowing the calculation of the distances between the target points reached (tip of the rod) and the planned target points (peaks of the cones). Using stereoscopy, it was possible to measure the necessary measurements with a measurement error of maximum 0.31 mm. Nine electrodes were inserted followed by target error measurement was performed. Figure ?? presents the model with *phantom* and Figure ?? presents images from the stereo camera used to calculate the

Electrode	1	2	3	4	5	6	7	8	9	Mean	Std.
Δ Target (mm)	1.52	1.35	2.7	1.6	2.49	2.31	1.1	1.85	1.43	1.82	0.21

Table 3 – Error in the positioning of target points planned and reached after surgery using a model with *phantom* and stereo camera to measure distances.

error. Table ?? presents the target error for each electrode, resulting in an average error of 1.82 ± 0.21 mm.

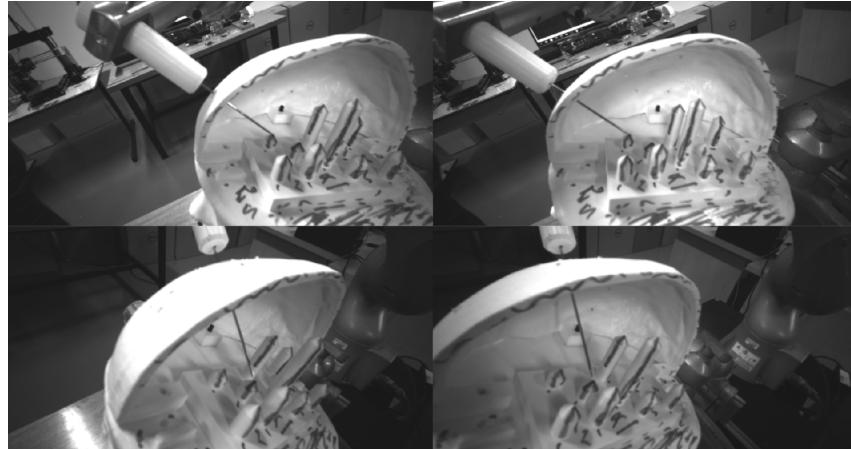


Figure 8 – Examples of images generated by the stereo camera for measuring the distance between the reached point and the planned target.

3 CONCLUSION

This chapter encapsulates the culmination of the research and development efforts dedicated to the Yara system, a novel robotic platform designed to enhance the precision and safety of Stereoelectroencephalography (SEEG) procedures. Throughout this work, we have meticulously detailed the intricate phases involved, from the initial patient monitoring and comprehensive SEEG planning to the critical robot registration and the precise execution of the surgical operation. Furthermore, a rigorous accuracy evaluation was conducted to validate the system's efficacy and reliability. The successful integration of advanced imaging techniques, sophisticated planning tools, and a collaborative robotic arm represents a significant stride towards improving outcomes for patients with drug-resistant epilepsy, offering a more controlled and accurate approach to electrode placement.

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