Objective Skill Analysis and Assessment in Neurosurgery by Using an Ultra-Miniaturized Inertial Measurement Unit WB-3

- Pilot tests -

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Abstract— **In recent years there has been an ever increasing amount of research and development of technologies and methods to improve the quality and the performance of advanced surgery. In several fields, such as laparoscopy, various training methods and metrics have been proposed, both to improve the surgeon's abilities and also to assess her/his skills. For neurosurgery, however, the extremely small movements and target operating space involved have prevented until now the development of similar methodologies and systems.**

In this paper we present the development of an ultra-miniaturized Inertial Measurement Unit (IMU) and its application for neurosurgery skill assessment in a simple pick and place scenario. This analysis is a preliminary yet fundamental step to realize a better training/evaluation system for neurosurgeons, and to objectively evaluate and understand how the neurosurgery is performed.

I. INTRODUCTION

IN recent years, more and more technologies have entered the operating theater. By using cameras or microscopes and miniaturized tools, surgeons are allowed to operate in smaller and smaller spaces, thus obtain better results and higher performance. While these new technologies have many advantages and benefits for patients, such as less pain and scarring, speed recovery, and reduced incidence of post-surgical complications, they often require surgeons to undergo long and difficult training [1]. Among the different challenges posed by neurosurgery, one of the most critical aspects is the objective evaluation of the surgical gesture. In other fields, such as laparoscopy for example, several metrics [2], and segmentation procedures [3] have already been proposed and employed to characterize different phases of surgical movements. The extremely small movements and target operating space involved in neurosurgery, however, have prevented until now the development of similar methodologies and systems. One possibility for the realization of compact measurement systems is offered by MEMS (Micro-Electro-Mechanical Systems) technology, offering multiple-axis response with high resolution and low power consumption in a single package. However, current prototypes such as WB-2 [4] or commercial systems (xSens MTx, InterSense InertiaCube3, and so on) are still too big and too heavy for application in neurosurgery.

Our aim, therefore, is to develop evaluation tools and to define a set of parameters that allow us to characterize the neurosurgeon's movements during neurosurgery operation. In this paper we present the development of an ultra-miniaturized Inertial Measurement Unit, named WB-3, and its application for the evaluation of the performance of neurosurgeons in a simple pick and place scenario.

II. MATERIALS AND METHODS

A. *Inertial Measurement Unit WB-3*

Our group recently developed a new IMU very compact and light weight (size 26 x 20 x 8 mm and weight 2.9 g). The IMU's extremely reduced weight and size allows it to be mounted on the bipolar forceps and to be used during normal tasks without disturbing the surgeon's performance (see next section for the details). A picture of the new IMU is shown in Fig. 1. The IMU is composed by the following sensors: 3-axis accelerometer LIS3LV02DL; 2-axis gyroscope IDG300; 1-axis gyroscope LISY300AL; and 3-axis Magnetometer HMC5843. IMU's characteristics are summarized in TABLE I.

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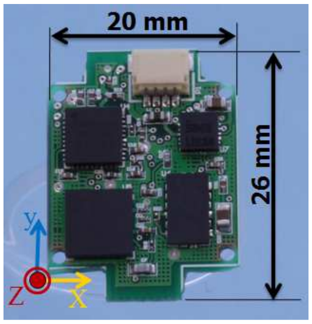

Fig. 1. Inertial Measurement Unit WB-3

TABLE I
MAIN CHARACTERISTICS OF THE SENSORS IN WB-3

	LIS3LV02DL	IDG300	LISY-300AL	HMC-5843
Range	±2 [g]	±500 [deg/s]	±300 [deg/s]	±4 [Gauss]
Sensitivity	12±1bit	12±1bit	12 ±1bit	12 ±3bit
Size	4.4 x 7.5 x 1 [mm]	6.0×6.0× 1.5 [mm]	7.0 x 7.0 x 1.9 [mm]	4.0 x 4.0 x 1.3[mm]
Bandwidth	40 Hz	140 Hz	88 Hz	50 Hz
Sample Rate	160 Hz	500 Hz	500 Hz	50 Hz
Linearity (FS)	±2%	<1%	±0.8%	±0.1%

The module contains also a 32 bit microcontroller STM32 Cortex (STMicroelectronics) for embedded signal elaboration. The communication between PC and IMU is performed using a CAN BUS at 1 Mb/s.

B. *Bipolar Forceps*

During neurosurgery, one of the most commonly used instruments is the bipolar forceps (Fig. 2) whose total length is 194 mm, tip length is 100 mm and weight is 34.0 g. A connector made by Acrylonitrile Butadiene Styrene (ABS) polymer in rapid prototyping for housing WB-3 is placed at the proximal end of the bipolar forceps.

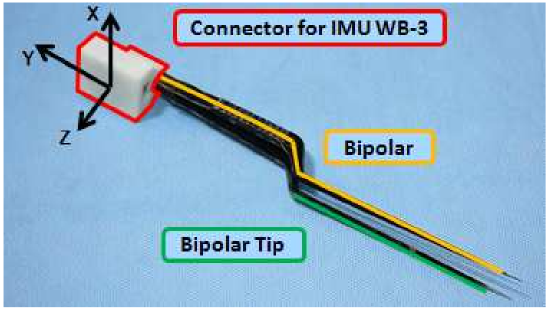

Fig. 2. Bipolar forceps used in our experiments.

C. *Training system*

The experimental setup is shown in Fig. 3. The microscope used during the experiments was a MITAKA MRI (Mitaka Kohki Co., Ltd, Tokyo, Japan). The different parts of the training system are shown in Fig. 4.

The training system is composed by five main parts:

1) Testbed: made by acrylonitrile butadiene styrene (ABS) polymer in rapid prototyping, simulates the typical surgical space during neurosurgery. Current version has a size of 60x40x60 mm, to simulate the most common operating space, which is usually around 40 to 60 mm in depth.

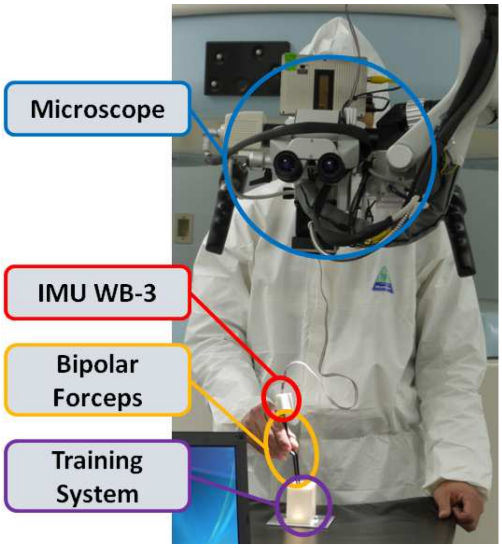

Fig. 3. Overview of the experimental setup

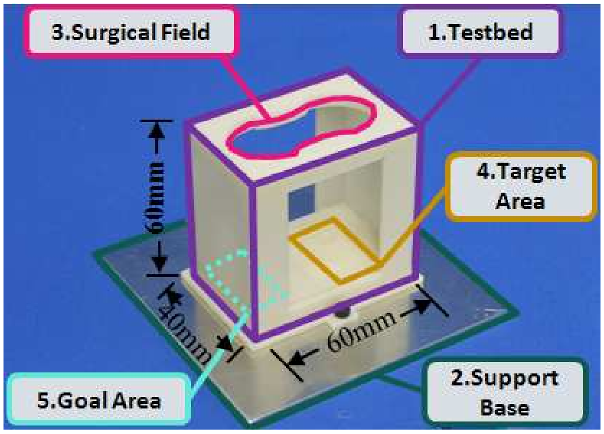

Fig. 4. Training system.

2) Support Base: is an aluminum base of 100 x 100 mm.

3) Surgical Field: simulates the aperture in the human skull. Its size is 50 x 19 mm. The subjects access the target area and the goal area from here.

4) Target Area: (See next subsection for details).

5) Goal Area: The targets picked up from the Target Area are put in the Goal area (size 10 x 30 mm).

D. *Target Area*

The Target Area is a replaceable soft surface (size 25 x 30 mm) on which the targets are placed before the experiment. The area is made by Hitohada skin-like gel RTV-2K#1406 Hardness 0 (EXSEAL Corp., Tokyo, Japan) which is a super-soft urethane resin for modeling which has very similar softness and feeling of human skin. Although the hardness of the model is different from the real brain tissue, we adopt it as a pilot study.

Three different types of target areas, each with 5 resistors randomly placed on it (Fig. 5), were prepared to simulate typical objects to be handled during neurosurgery: (A) BIG: 3.2 x 1.6 mm SMD resistor; (B) MEDIUM: 2.0 x 1.2 mm SMD resistor; (C) SMALL: 1.0 x 0.5 mm SMD resistor. These different sizes of resistors used to simulate the typical neurosurgery objects were approved by neurosurgeon.

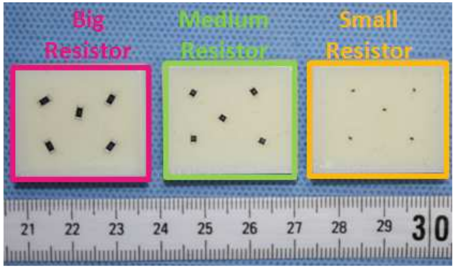

Fig. 5. Three types of target area, each with 5 targets randomly placed on them.

E. *Subjects*

Thirteen non-medical subjects (Average age 27.53 years, age range 22-39, all male, all right handed) and one professional neurosurgeon (subject #14, age 40) kindly agreed to participate to the experiments after providing informed consent. Among the non-medical subjects, only one subject (subject #9) had some experience with neurosurgical tools, and one subject (subject #2) had some experience with laparoscopy; all the other subjects were totally novice.

F. *Experimental protocol*

The experimental setup is shown in Fig. 3. The subject looks trough the microscope at the evaluation system. The experiments consist of picking up all the targets from the target area, with the bipolar forceps, and releasing them in the goal area, one by one. In total there are 15 target areas (3 sizes x 5 repetitions), and they are replaced by following the order BIG → MEDIUM → SMALL, repeated 5 times.

G. *Data saving and pre-processing*

The WB-3 is connected through a CAN-USB converter to a standard PC. Acceleration data are sampled at 160 Hz, gyro data at 500 Hz, and Magnetic data at 50 Hz. Data were acquired on the PC for real-time display, and saved for storage and offline analysis. All the data were saved as CSV (Comma Separated Value), and they loaded in Matlab^{TM} (The MathWorks, Inc.) for further processing and analysis.

The start/stop time of the trial was decided by the direction of Y axis which was almost aligned to the gravity direction when the subject started and finished the trials. Therefore, the raw data were trimmed to remove dead-time at the beginning and at the end of the trial due to the manual start/stop as follows: beginning is defined as the first sample when the acceleration value of Y axis $|a_y| > 9.1$ m/s^2; end is defined as the first sample from the end when $|a_y| > 9.1$ m/s^2. Y is the vertical axis of the bipolar forceps (Fig. 2).

The acceleration and rate-gyro raw data were converted respectively in m/s^2 and deg/s using the following bias and gain for values: $\text{Gain}_{acc} = 9.81$; $\text{Bias}_{acc} = 1024$; $\text{Gain}_{gyro\ (x\text{-}y)} = 0.244$; $\text{Bias}_{gyro\ (x\text{-}y)} = 2048$; $\text{Gain}_{gyro\ (z)} = 0.146$; $\text{Bias}_{gyro\ (z)} = 2048$. The magnetic raw data was used directly to show the different orientation of subjects' hands in 3D space during the trials and the different distribution.

Acceleration components, angular speed components and magnetic components were then filtered and smoothed by using a 10th order bandpass IIR Butterworth filter with cutoff frequencies fc1 = 0.05 Hz, fc2 = 8Hz (accelerometer and magnetometer), fc1 = 0.05 Hz, fc2 = 5 Hz (gyroscope), to remove bias and to remove physiological tremor [5].

III. EXPERIMENTAL EVALUATION

The following sections present only the details about the experimental evaluation for the MEDIUM target due to the space limitation. In particular, the following variables were calculated and analyzed: execution time T_{task}; Mean, Power Spectral Density (PSD) of acceleration value $|a|$; Mean, Cumulative Distribution of angular speed $|\omega|$; and space distribution of magnetic value $|H|$. Several other parameters such as Jerk $|J|$, etc, were also calculated; however their analysis require a longer discussion. In the following figures, (norm.) indicates that the data have been normalized to the average corresponding data of the surgeon (subject #14) for an easier visual comparison of the scales.

A. *Analysis of execution time*

The surgeon proved to be faster (lower T_{task}) and showed fewer variations in the execution time of the tasks than all the novices, as shown in Fig. 6.

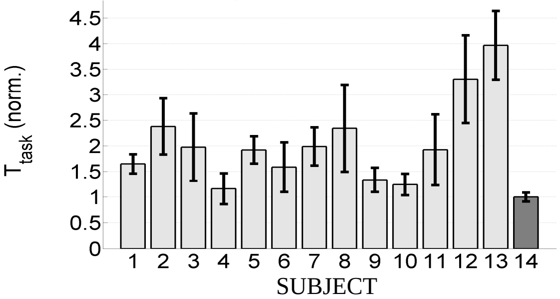

Fig. 6. Execution time for MEDIUM targets, averaged on 5 trials for each subject. Normalization value for surgeon is 11.8 s.

B. *Analysis of accelerometer*

As can be seen in Fig. 7, the mean acceleration executed by surgeon is usually less than the other subjects. Subject #2 has a lower mean value of acceleration than the surgeon; however, his deviation value is bigger than surgeon's.

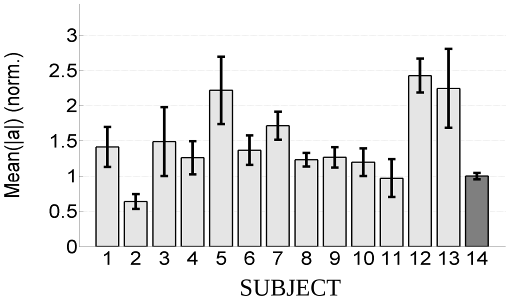

Fig. 7. Mean acceleration for MEDIUM targets, averaged on 5 trials for each subject. Normalization value for surgeon is 0.63 m/s^2.

The Fast Fourier Transformation (fft) for acceleration $|a|$ was calculated with FFTsize = 8192 samples and frequency resolution $f_{res(a)} = f_a /$ FFTsize $= 160/8192 = 0.0195$ Hz. The PSD was estimated with the following formula: $(\text{fft} \cdot \text{conj}(\text{fft}))/\text{fft}_{size}$. The evaluation is done in the [0.2 – 8] Hz frequency range.

As can be seen in Fig. 8, the mean PSD clearly separates the experienced neurosurgeon respectively from the other subjects, whose mean PSDs were usually much higher.

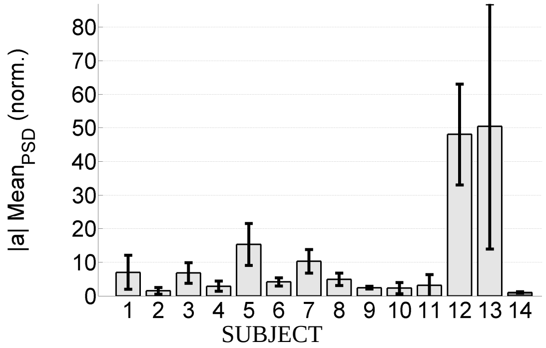

Fig. 8. Mean power of the acceleration for MEDIUM targets, averaged on 5 trials for each subject. Normalization value for surgeon is 0.68 $(m/s^2)^2$.

C. *Analysis of gyroscope*

As can be seen in Fig. 9, the mean angular speed executed by ssurgeon is usually less than the other subjects. Subject #2 has a lower mean value of angular speed than the surgeon but has a bigger deviation value than surgeon.

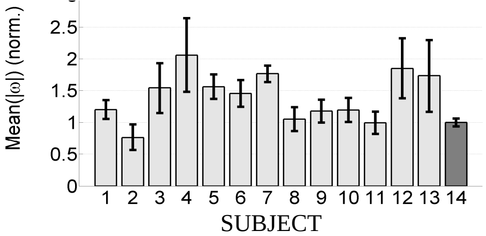

Fig. 9. Mean angular speed for MEDIUM targets, averaged on 5 trials for each subject. Normalization value for surgeon is 5.93 deg/s.

Among the different parameters, the Cumulative Distribution Function (CDF) of the angular speed $CDF(\omega)=P(X\leq\omega)$ evaluated for X=95% ($CDF_{95\%}$) shows some difference between the surgeon and the novices (Fig. 10). Surgeon's $CDF_{95\%}$ is usually lower than the other subjects; more important, it shows a very limited variance, thus signifying high regularity in the exercises.

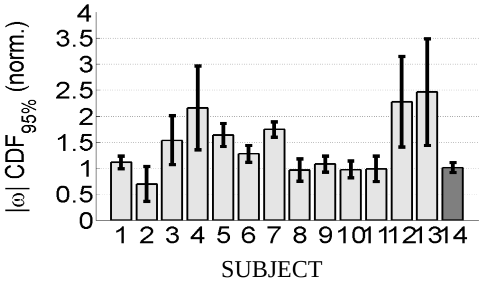

Fig. 10. Cumulative distribution function (CDF) of the angular speed for MEDIUM targets. Normalization value for surgeon is 17.2 deg/s.

D. *Analysis of magnetometer*

The data of magnetometer are originated by the earth magnetic field which can be used to measure the orientation of magnetic sensor. In Fig. 11 are showed the raw data distribution of magnetometer in 3D space for the Surgeon, subject #9 and subject #1. As can be seen in Fig. 11, the raw data distribution among surgeon, subject #9 and subject #1 are different due to the different gestures and movements of their hands during the trials. And the distribution executed by surgeon is more concentrated than other two subjects which means that the variance of surgeon's movement is more limited.

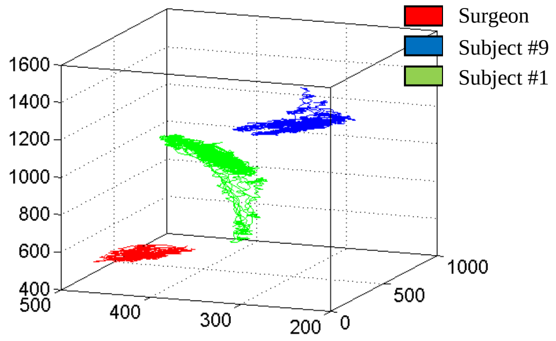

Fig. 11. Raw data distribution of magnetometer for MIDIUM targets from surgeon, subject #9 and subject #1.

IV. CONCLUSIONS

In this paper we presented the development of an ultra-miniaturized Inertial Measurement Unit named WB-3 suitable for applications in neurosurgery due to its very low size and weight, and its high performance. The preliminary results proved that the IMU's data could present different performance between a professional neurosurgeon and a group of novices, therefore validating the proposed approach. These analysis and modeling, moreover, are an important step towards the automatization and the robotic assistance of the surgical gesture.

Currently, work is still in progress, and our future commitment in this field is to continue to analyze the performance of surgeons in more complex procedures and with other sensor systems.

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