Experimental Measurement of Information Transfer Rate of the Inertial Sensor Based Human-Computer Interface for the Disabled

JOSIP MUSIĆ, MOJMIL CECIĆ, MIRJANA BONKOVIĆ
Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture
University of Split
Ruđera Boškovića bb
CROATIA
jmusic@fesb.hr http://labacs.fesb.hr

Abstract: - The paper presents inertial sensor based human-computer interface for the disabled. The device uses commercially available inertial sensor pack to reliably measure 3D head orientation (via Kalman filtering of accelerometer, gyroscope and magnetometer measurements) which is then transformed into appropriate control signal(s) depending on the intended application scenario. In order to measure information transfer rate (or throughput) of the device, application to computer pointer control is explored. Initial study on the subject was achieved in our earlier work [1] where number of application issues were identified. The current paper deals with possible solutions to some of the issues by introducing additional signal conditioning algorithms and examines their influence on device comfort and throughput as the two most important performance parameters. Obtained information transfer rates are presented and compared to values from the initial study and to values of some widely used interfaces such as trackball or joystick (found in the literature). The effects of proposed improvements are discussed and conclusions are drawn.

Key-Words: - human-computer interface, throughput, inertial sensors, accelerometer, gyroscope, magnetometer

1 Introduction

Number of people in the world suffering from some kind of limb impairment or paralysis is constantly increasing. The most common cause of paralysis is traumatic spinal cord injury. In the United States alone in 2002 there were 250 000 subjects with paraplegia or tetraplegia with estimated 11 000 new cases each year [2]. According to just released study [2] the number is currently at 259 000 with 12 000 new cases each year. From the total number of the disabled (in the year 2002) around 52% were paraplegics and around 47% were quadriplegics (whom are the target group of our research). It is also interesting to note that Council of Europe Parliament Assembly in its report from 2002 [3] estimated the number of people suffering from traumatic spinal cord injuries in member states (which then numbered 15) to be around 330 000 with 11 000 new cases every year.

If structure of the disabled is examined it can be seen that around 56% of the disabled sustain their injuries between the ages of 16 and 30. This is significant because individuals are then usually at the beginning of the period of highest financial productivity as well as at the peak of their physical strength. According to [2] around 76% of quadriplegics in the United States are still unemployed 8 years after sustaining their injuries with medical costs as high as 659 000 USD in the first year. Paralysis thus presents significant financial as well as psychological cost to the loved ones of the disabled and to the society in general. It is considered that even moderate improvement in medical condition of the disabled would decrease cost of their care significantly. In our current research we are not concerned with improving medical condition of the disabled but improving quality of their life through increase of independence. Due to ubiquitous nature of computers they present a sound choice for the purpose of providing the disabled with higher level of independence. Typical human-computer interfaces are designed and developed with healthy subjects in mind. These systems often require some kind of physical interaction usually with hands, and are thus not appropriate for quadriplegics. There exists number of specialized human-computer interfaces designed for this target group which track movement of body part over which the disabled person has voluntary control and transform these movements in appropriate signals to control computer or any other device (e.g. wheelchair). Video based techniques [4, 5, 6, 7, 8, 9] are arguably the most popular and have benefits such as low price and no need for specialized equipment. Unfortunately they are also characterized with drawbacks inherent to video based methods (e.g. sensitivity to lightning conditions and shadows, limited field of view, etc.). Video based techniques usually employ one or more cameras (either in visible or infrared spectrum) to identify and track body parts usually with the aid of markers attached to that body part, although markerless system also exist. Good example of video based human-computer interface is [4] in which Betke et. al. developed *"Camera Mouse"*, the system based on single camera that tracked user movements for the purpose of controlling computer screen pointer. The tracking algorithm was based on template matching using correlation and constant template updating. The system tracked user defined body landmarks (e.g. eyes or lips). Testing was achieved with 20 healthy subjects and 12 subjects with some kind of motor dysfunction. Authors used measurement time as main performance parameter and concluded that in general the proposed system is slower compared to standard computer mouse but presents portable and usable system for the disabled. Another possible application of the video techniques is to track pupil movements [8, 9] where solution of *Midas touch problem* is important (i.e. distinguishing between intentional and unintentional eye fixation). In [9] Chin et. al. used near-infrared light-emitting diodes to illuminate the eye of the subjects and a video camera to record the eye image. Video image data (sampled at 120 Hz) was processed by eye tracking algorithm which performed feature recognition as well as estimation of point of gaze. The algorithm also determined whether a fixation had occurred by evaluating the data based on user defined criteria. The loss of data of up to 200 ms in duration was accommodated due to eye blinking. The described video based interface was a subsystem of a more complex system also incorporating electromyogram (EMG) measurements. This kind of fusion of different measurement systems showed to be very promising and accurate, overcoming shortcomings of individual subsystems [9, 10, 11, 12]. Movement of any body part over which the disabled person has control can be identified and tracked using number of different measurement techniques (other than video based techniques) such as ultrasound and tilt sensors [13, 14, 15, 16]. As an example of interfaces based on tracking human movement and their diversity, work of Huo et. al. [15] can be considered. In the work wireless tongue operated device named *Tongue Drive System* was introduced. A small rare-earth permanent magnet was placed on the tip of subject's tongue and its movement was detected by an array of magnetic field sensors placed on a headset outside the mouth or on an orthodontic brace inside the mouth. Effects of external magnetic field disturbances were compensated for with usage of reference electronic compass placed on top of subject's head. During training phase *principle component analysis* was used to extract important signal features and thus form cluster space. The *k-nearest neighbor* algorithm was used for classification purposes. The system was tested on healthy subjects with information transfer rate (ITR) of 2 bits/s and accuracy higher than 90%.

Human biopotentials (such as electroencephalogram or EEG, electromyogram or EMG and electrooculogram or EOG) can also provide source of control signals for the computer [10, 17, 18, 19]. These systems require specialized equipment which is often very expensive and measures minute signals (magnitude order of μV in case of EEG) which are easily corrupted with noise. Also limited number of distinct control signals (usually 2 or 3) can be used [18]. This kind of systems (especially EEG based systems) are usually used when the subjects is totally paralyzed or locked in, as in case of Amyotrophic Lateral Sclerosis (ALS). Example of such a system can be found in work of Blinkertz et. al. [17] where Berlin brain-computer interface for actuated spelling via Hex-o-spell (specially designed graphical user interface) was constructed. The Berlin computer interface operated based on spatio-spectral changes in EEG signals during motor imagination. Machine learning algorithms were implemented to achieve better feedback based on user specific brain signature. Hex-o-spell spelling interface combined probabilistic data and dynamic system theory to achieve character selection. Language model was used to rearrange the character layout to reduce required selection time. Reported typing speed results measured on two healthy subjects ranged from 2.3 char/min to 7.6 char/min.

Voice based human-computer interfaces are also very popular both for able bodied and disabled subjects. These systems are characterized with good communication bandwidth when functioning properly and some significant drawbacks such as sensitivity to background noise and the fact they are language specific. Examples of such systems can be found in [11, 20].

The one best human-computer interface for the disabled does not exist and the decision which interface should be used is complex [21] and is based on number of parameters: price, learning curve, user preferences and medical condition, area of application, etc. Regardless of selection, significant statistical dependence between interface performance and user comfort and satisfaction was observed.

We believe there exists the need for a new kind of interface which would be easy to use, highly portable, robust and affordable. In our pervious work [1] we have proposed inertial sensor based pointing device which used commercially available sensor packs [22] to track 3D head orientation and map measured angles to pointer screen coordinates. The advantages of the system in our opinion included high portability, simple calibration and data processing algorithms as well as independence of external signal sources (since Earth gravitational and magnetic fields are ever-present). The proposed system was tested on healthy subjects with throughput (during multidirectional point-and-select task) as the main performance parameter. Obtained throughput values depended on applied control scheme and selection technique, with maximum value of 1.93 bits/s (compared to 3.8 bits/s for standard computer mouse obtained during the same study). User feedback was also positive with number of suggestions for possible improved comfort and performance. Some of the suggestions were identified as important and were applied to the system. The paper introduces these improvements and examines how they influence the performance (throughput and comfort assessment).

The article is structured as follows. Section two presents an overview of the proposed system hardware as well as applied signal conditioning algorithms. Experimental procedures and protocols are presented in section three, while section four presents obtained measurement results followed by analysis and discussion. Finally, some conclusions are drawn, and future research directions are proposed.

2 System design

The proposed system was based on MTx inertial/magnetic sensor pack manufactured by XSens Motion Technologies, The Netherlands [22], depicted in Figure 1. The sensor pack was positioned on top of the subjects head (Figure 2) and used Kalman filtering techniques to fuse 3D measurement data from accelerometers, gyroscopes and magnetometers to provide reliable and accurate 3D orientation estimation as indicated in Table 1 (in the present study only yaw and pitch angles defined in Figure 2, were used).

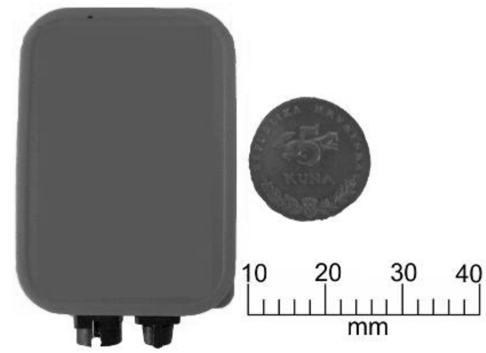

Fig. 1 – MTx sensor

Small dimensions and weight (38 x 53 x 28 mm and 30 g) made this sensor suitable for the proposed application. Sensor was connected to computer via XBus Master (also from XSens Motion Technologies), a digital data bus with signal conditioning capabilities. Although, XBus Master enabled battery power supply and wireless connection to computer via Bluetooth (and thus provided high portability) USB based connection and 220V power supply were used in the present study. Sampling frequency of XBus Master in all experiments was set to 100 Hz. Elastic harness was used to ensure snug fit to subject's head and prevent sensor from moving during the measurements.

Table 1 – MTx sensor technical specifications

MTx inertial/magnetic sensor		
Static accuracy	roll/pitch	< 0.5^o
	yaw	< 1^o
Dynamic accuracy		2^o RMSE*
Angular resolution		0.05^o
Power consumption		350 mW
Ambient temp. range		-20^{o}C - +60^{o}C
XBus Master		
Max. No. of sensors		10
Sampling frequency		10 – 512 Hz
Typical radio range		100 m

* **R**oot **M**ean **S**quare **E**rror

Experimental setup also included 20'' wide LCD monitor (LG L204WT – SF set to 1680 x 1050 pixel resolution), as well as Trust GM – 4200 optical mouse which was used as a referent input device.

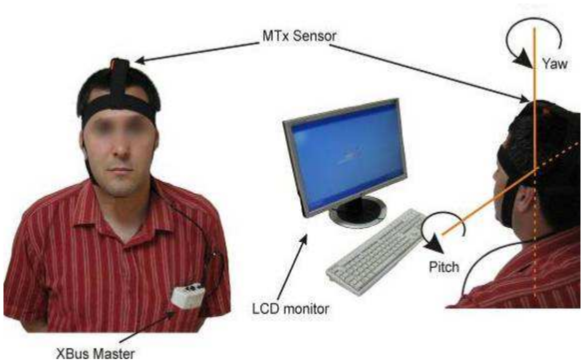

Fig. 2 – Sensor positioning and angle definition

2.1 Calibration procedure

At the beginning of each measurement trial for a particular subject, calibration procedure was performed in order to account for small variations in sensor positioning as well as user posture, distance from the monitor and other measurement specific conditions. The calibration procedure was simple and could be completed under 30 seconds. The procedure required the user to turn his/hers head and look at three dots on the monitor. Dot positions were predefined and were located at center of the screen (840,525), the left most point on the screen (0,525) and at the top most point on the screen (840,0) as depicted in Figure 3 (red dots).

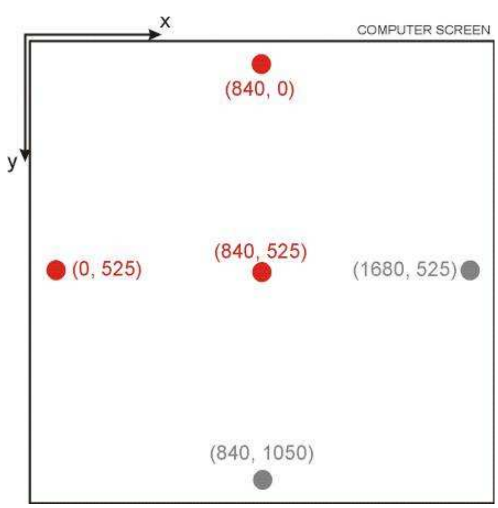

Fig. 3 – Definition of calibration dots

The assumption made was that the subject sitting comfortably with his/hers eyes looking straight forward and facing the monitor was looking at center dot. Thus this head position was named neutral, and measured yaw ($\psi_{CNeutral}$) and pitch ($\varphi_{CNeutral}$) angles neutral head angles. The dot on the left most part of the screen was used to measure maximum yaw angle (ψ_{CLeft}), while the dot on the top part of the monitor enabled measurement of maximum pitch angle (φ_{CTop}). Assumption of symmetry of head range of motion (RoM) around neutral point was adopted. Better accuracy could be achieved if additional two dots are used but at expense of longer calibration time. The new dots should be symmetrical to left and top dot in respect to vertical and horizontal line going through central dot and thus would completely define head RoM making assumption about symmetry of head RoM unnecessary and allowing for RoM asymmetry. The positions of suggested new dots are depicted in Figure 3 (grey dots). Based on recorded angle values and screen resolution, pixel/angle ration was defined as

$$R_x = \frac{1680}{2 \bullet |\psi_{CNeutral} - \psi_{CLeft}|} \quad (1)$$

for x direction, while the same ratio for the y direction was defined as

$$R_y = \frac{1050}{2 \cdot |\varphi_{CNeutral} - \varphi_{CTop}|} \quad (2)$$

With knowledge of R_x and R_y any yaw-pitch angle combination could be mapped into computer monitor coordinates, and screen pointer moved accordingly.

2.2 Signal conditioning

Based on user feedback during the first study, two signal conditioning algorithms were implemented (in a manner similar to [23]) for both pointer and joystick control schemes, as well as visual feedback for joystick control mode (for details on control schemes reader is referred to [1]). The signal flow in current system version can be seen in Figure 4.

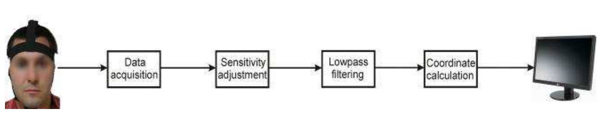

Fig. 4 - Signal flow overview

2.2.1 Sensitivity adjustment

During initial study participants often complained that recorded calibration angles were either too big or too small (depending on pointer control scheme and user preferences) yielding poor pixel/angle ratio and causing subject discomfort while using the device. This problem was avoided in current system version by introduction of interactive control (i.e. slider) by means of which the user could, at any time, adjust sensitivity to desired level. This feature was used under controlled conditions in the study in order to keep measurement variables the same throughout the entire measurement process (i.e. sensitivity was, if needed, adjusted and tested at the beginning of the measurement by each subject and was kept at that level for the remainder of the measurement). The slider control had direct effect on de-numerator in Equations (1) and (2) through change of ψ_{CLeft} and φ_{CTop}, respectively. This in turn re-adjusted head RoM values. It should be noted that current system version enabled change in R_x and R_y by the same factor/coefficient i.e. sensitivities in *x* and *y* directions were coupled and could not be re-adjusted independently.

2.1.2 Lowpass filtering

Another issue identified in initial study was pointer jitter in pointer control mode in situations where subject was required to achieve finer head movements. Two sources of jitter were identified in subsequent analysis: 1) head tremor, and 2) small calibration angles (i.e. high sensitivity). The problem of high sensitivity was tackled with previously mentioned sensitivity adjustment feature, while effects of head tremor were alleviated by means of real time lowpass filtering with adjustable cut-off frequency and attenuation level (via interactive slider controls). Biquadratic (or biquad) filter architecture [24] was used. This filter architecture had the following transfer function in z-domain

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}} \quad (3)$$

where a_0, a_1, a_2, b_0, b_1 and b_2 are filter coefficients calculated based on desired filter properties (e.g. cut-off frequency). This filter architecture was used due to its simplicity (low number of filter coefficients) and good performance obtained during trials. The designed filter was then implemented in "Direct Form 1" manner using the equation

$$y_t = \frac{b_0}{a_0} x_t + \frac{b_1}{a_0} x_{t-1} + \frac{b_2}{a_0} x_{t-2} - \frac{a_1}{a_0} y_{t-1} - \frac{a_2}{a_0} y_{t-2} \quad (4)$$

where x_t, x_{t-1} and x_{t-2} are filter input signals at times *t*, *t-1* and *t-2*, respectively, while y_{t-1} and y_{t-2} are filter outputs at times *t-1* and *t-2*. This means, that only four variables need to be stored in memory at any given time making this architecture suitable for applications were system resources are limited.

In order to demonstrate effectiveness of the proposed lowpass filtering we instructed one of the subjects to keep the screen pointer inside small (20 pixel diameter) circle target (marked with blue in Figure 6) as steady as possible. Figure 5 depicts raw and filtered data for *x* coordinates during the experiment. Elimination of jitter can clearly be seen as well as small latency (i.e. phase shift) which is introduced by filtering process.

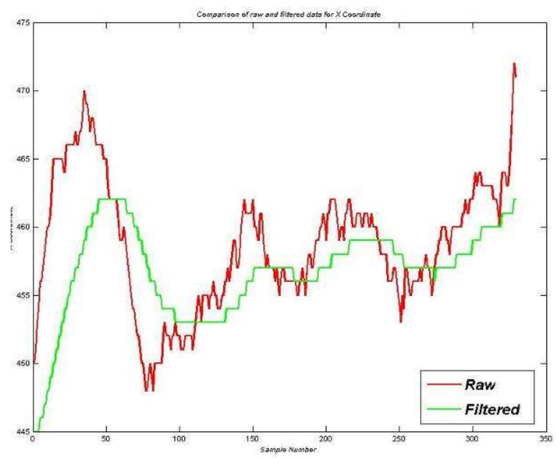

Fig. 5 – Comparison of filtered and unfiltered screen pointer coordinates

Figure 6 depicts more clearly obtained improvement in screen pointer precision. The red line represents pointer trajectory without any filtering while the green one represents pointer trajectory with lowpass filtering and cut-off frequency determined by the user. From the figure it is clear that lowpass filtering enables more precise movement as the trajectory is more compact and exits the target area less frequently and with smaller amplitudes then the raw data trajectory.

2.2.3 Visual feedback

In order to provide visual feedback to users as to where they were in control space while the device was in joystick control mode, *"motion radar"* was designed and implemented. Please note that joystick control space was changed in comparison to [1]. In current system version it was based on circular shaped design (as depicted in Figure 7), while in the first version it was based on square shaped design.

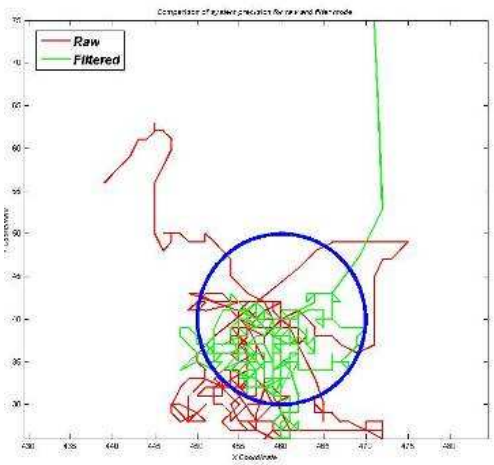

Fig. 6 – Comparison of pointer positioning precision for raw and filtered mode

The movement resolution in joystick mode was set to 1^{o} highlighting the need for motion radar. The illustration of joystick mode control space with 1^{o} resolution and different speed levels for each pointer direction is depicted in Figure 7. Different colors represent different speed levels while black lines and circles represent direction and speed level borders, respectively.

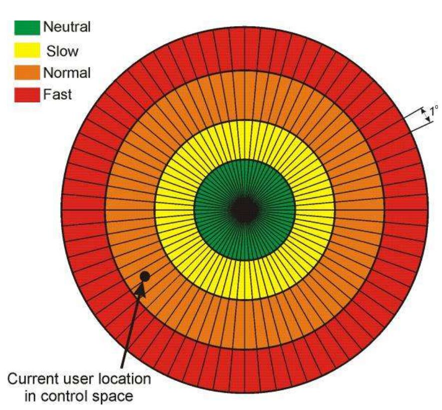

Fig. 7 – Illustration of joystick control space

Thus the information content which needed to be relayed to the user included the following: 1) what is the current speed level of the pointer, 2) how far from the next speed level (either lower or higher) user was, and 3) in what direction the pointer would go based on current head pose. These design requirements needed to be implemented in such a way that user didn’t have to divert attention from the pointer itself. The proposed system is depicted in Figure 8.

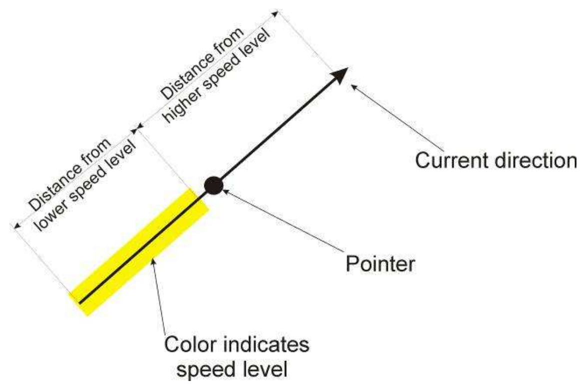

Fig. 8 – Visual feedback in joystick mode

The arrow length is constant and its direction indicates current direction of pointer movement. The color of arrow bar depends on current speed level while bar length indicates distance from next speed level (either lower or higher) as depicted in Figure 8. The arrow moves with the pointer enabling the user to keep focus on task at hand while providing required feedback.

3 Experimental setup

Experimental design used in the study was based on multidirectional point-and-select task adopted from [25] which in turn was based on ISO 9241-9 standard (*Ergonomic requirements for office work with visual display terminals: Requirements for non-keyboard input device*). It should be noted that the same design was used in our initial study thus enabling comparison of results. Measurement data recording from MTx inertial/magnetic sensor was achieved using in-house software written in Visual C#. After completing the measurement, each test subject was given two identical questioners (one for each pointer control mode) in which they had to rate device comfort.

3.1 Test subjects

Fifteen volunteers (11 male and 4 female) recruited among faculty staff and students participated in the study. All were everyday computer users and have never used a hands-free pointer device (except in our initial study). All participants were healthy and didn’t suffer from any cervical spine injury which could affect the results. Participants age ranged from

21 to 41 years (mean 26.2). It should be noted that 12 subjects participated in the initial study while 3 subjects were completely new to the system.

3.2 Throughput

The main performance parameter used in the study which takes into consideration both the speed and accuracy of executed multidirectional point-and-select task is throughput. Throughput is defined as

$$T = \frac{ID_e}{MT}\left[\frac{bits}{s}\right] \qquad (5)$$

where MT is measurement time and ID_e is effective index of difficulty defined as

$$ID_e = \log_2\left(\frac{D}{W_e + 1}\right) \qquad (6)$$

where D is the distance between home position and center of the target and W_e is effective target width. Effective target width is defined as

$$W_e = 4.133 \cdot \sigma \qquad (7)$$

where σ is standard deviation in selected target coordinates. The definition of effective target width is valid only under assumption of error rate (percentage of unsuccessful target selections) being under 4%. If this is not the case, equation needs to be adjusted according to Gaussian probability density function.

3.3 Independent variables

The main independent variable in the study was input technique which had five possible states:

1.) Mouse (M)
2.) HeadJoystick in Pointer mode with Keyboard (HJPK)
3.) HeadJoystick in Pointer mode with Time trigger (HJPT)
4.) HeadJoystick in Joystick mode with Keyboard (HJK)
5.) HeadJoystick in Joystick mode with Time trigger (HJT)

Minimization of learning effects was achieved by counterbalancing input techniques using 5x5 balanced Latin square depicted in Figure 9. The M technique was included into the study to provide baseline throughput value through which validation of experimental procedures and experimental design with similar studies (e.g. [25, 26, 27]) could be achieved.

Participants 1,6,11	1	2	5	3	4
Participants 2,7,12	2	3	1	4	5
Participants 3,8,13	3	4	2	5	1
Participants 4,9,14	4	5	3	1	2
Participants 5,10,15	5	1	4	2	3

Fig. 9 – 5x5 Balanced Latin square

In the joystick control mode, pointer could move in 360 directions (i.e. 1^o resolution) with three speed levels depending on the current head pose. In the pointer mode current yaw and pitch angles were directly mapped onto screen coordinates. For the details of each control mode (joystick and pointer) please refer to [1]. Please note existence of two selection techniques: keyboard (via spacebar key) and time trigger (condition of pointer being inside the target for 400 ms).

Also, three additional independent variables were used:

- target circle width (W): 20 and 60 pixels,
- distance (D): 300 and 420 pixels,
- trial (i.e. target number): 1 to 16

Taking into account all the independent variables 4800 trials were recorded (15 test subjects x 5 input techniques x 2 circle widths x 2 distances x 16 trials).

3.4 Measurement procedure

Before the measurements participants were briefed on measurement procedures and study objectives, and informed consent was obtained. Test subjects were seated comfortably in front of computer screen at approximate distance of about 80 cm. At the start of every measurement for particular test subject calibration procedure described in Section 2.1 was performed.

Measurement GUI can be seen in Figure 10. Test subjects were required to position the pointer inside home circle highlighted in green (while the next target was highlighted in purple) and select it (either with keyboard or time trigger). Then the target circle previously highlighted in purple changed its color to red (i.e. became active) and the user was required to, as quickly and as accurately as possible, to position the pointer inside the target circle and select it. After the selection was made the home circle again became highlighted in green and the next measurement trial ensued.

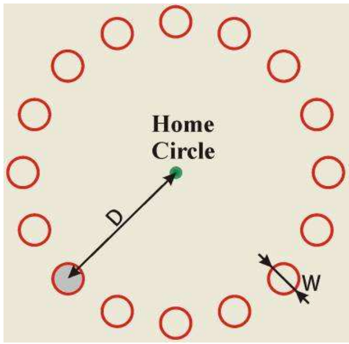

Fig. 10 – Measurement GUI

After successful completion of measurements, each test subject was given two identical questioners (one for each pointer control scheme). The questions contained in the questioners were the same as in our original study and were adopted from [25]. The main purpose of the questioners was to provide insight into device comfort with marks ranging from 1 (worst possible score) to 7 (best possible score). The questions are listed in Table 2.

Table 2 – Comfort assessment questioner

No.	Question
1.	Would you like to use HeadJoystick device?
2.	General impression compared to the mouse?
3.	Neck fatigue
4.	Eye fatigue
5.	General comfort
6.	Pointing speed
7.	Target selection
8.	Accurate positioning
9.	Physical effort
10.	Mental effort
11.	Movement smoothness
12.	In general, the device usage was…

4 Results and discussion

Obtained baseline throughput for computer mouse was found to be in agreement with throughput values found in literature (although close to the upper limit) indicating validity of used experimental design. ANOVA testing indicated there was significant effect ($p < .001$) of Input Techniques on the measured throughput values.

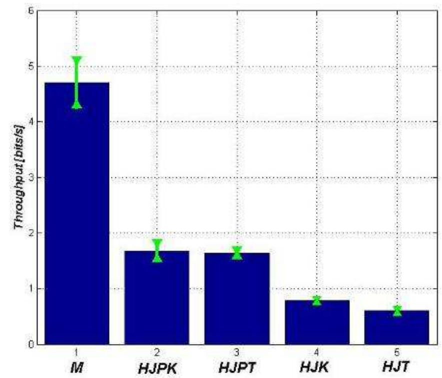

Fig. 11 – Throughput results

Figure 11 depicts measured mean throughput values (with their standard deviations) for all tested devices and all selection schemes and control modes. The largest throughput was recorded for computer mouse (M) measuring 4.7 bits/s. Compared to our initial study (3.8 bits/s) this value is higher but is still in range of values reported in the literature and also within standard deviation interval reported in the initial study. The variability in mouse throughput needs to be studied further but we believe that user experience with used experimental design from the initial study had significant effect. The proposed inertial sensor based device measured 1.68 bits/s in pointer control mode and 0.78 bits/s in joystick control mode. These values are smaller than the ones from initial study by 0.14 bits/s for joystick mode and 0.25 bits/s for pointer mode. The difference could partially be explained by introduced improvements on two levels: 1) the nature of improvements could lower obtainable throughput, and 2) the subjects (although familiar with first system version) were not accustomed to improved system. As in the first study, pointer control mode proved to be the better of two control schemes with higher throughput values and with more positive user feedback. The users had some difficulties maneuvering the screen pointer in the joystick mode. In fact, some of the participants noted high sensitivity in direction selection (due to 1^o resolution) and expressed belief that if resolution was smaller (e.g. 5^o) they could more easily control the pointer and achieve better performance. For comparison purposes we now list throughput values for some widely used human-computer interfaces: 3 bits/s for trackball, 2.9 bits/s for touchpad and 1.8 bits/s for joystick [25, 26, 27].

Two additional performance parameters which provide improved insight into measurement results are measurement time and error rate, whose mean values and associated standard deviations are depicted in Figure 12 and Figure 13, respectively.

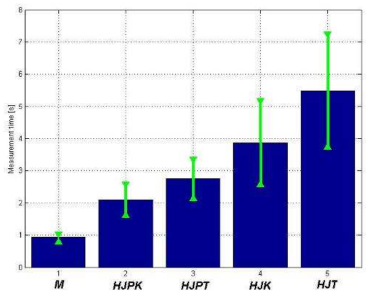

Fig. 12 – Measurement time

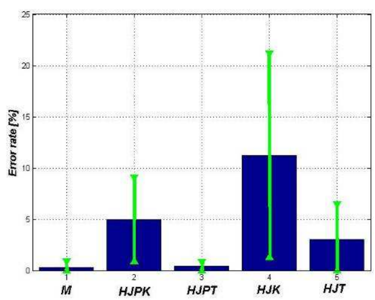

Fig. 13 – Error rate

Figure 12 indicates that measurement time is smaller in the pointer mode and that keyboard selection technique is faster of the two selection techniques. At the same time Figure 13 indicates that, although faster, keyboard selection has larger error rates as compared to time trigger technique. Thus, selection technique has small or no influence on final throughput as can be seen in Figure 6. Comparison of recorded throughput as well as measurement time and error rates between initial and current study are presented in Table 3.

Table 3 – Comparison of study results

Study		**Throughput [bits/s]**	**MT [s]**	**ER [%]**
Initial	J	0.92	4.805	3.8
	P	1.93	2.73	4.8
Current	J	0.78	4.68	7.1
	P	1.68	2.42	2.7

P – Pointer mode; J – Joystick mode

The table indicates that measurement times are lower in the second study while error rates are higher for joystick mode and lower for pointer mode. Increase in joystick mode error rate could be explained by before mentioned high sensitivity resulting in small pointer movements just before the selection was made. It should be noted that in time trigger selection mode false selection was recorded if user didn't complete the selection process within specified time limit which was arbitrarily set to 8 s.

It is also worth noting the observation which surfaced during the development of the current system version (and not during the measurements themselves). The throughput values obtained for the same subjects (four of them in total) were significantly higher for the pointer mode (2.8 bits/s) when only low pass filtering (and not the sensitivity adjustment) was used, but at the expense of small (controllable) jitter, while they were similar for the joystick control mode (0.85 bits/s). Implementation of lowpass filtering (with adjustable attenuation level) demonstrated one significant drawback: displacement of neutral head position defined by neutral yaw and pitch angles ($\psi_{CNeutral}$ and $\varphi_{CNeutral}$, respectively) thus causing some user discomfort. This effect needs to be compensated for in future system version. The full impact of applied improvements can be seen in comfort assessment results presented in Figure 14 and Figure 15 for joystick and pointer mode, respectively.

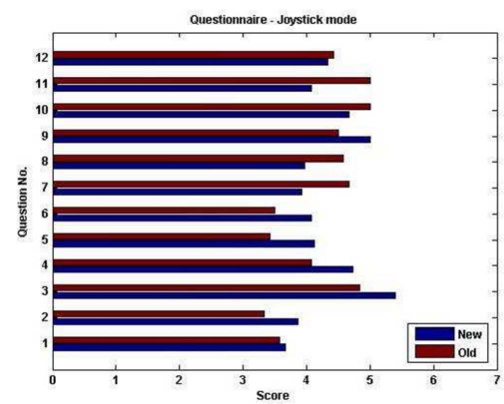

Fig. 14 – Comparison of questionnaire results for joystick mode

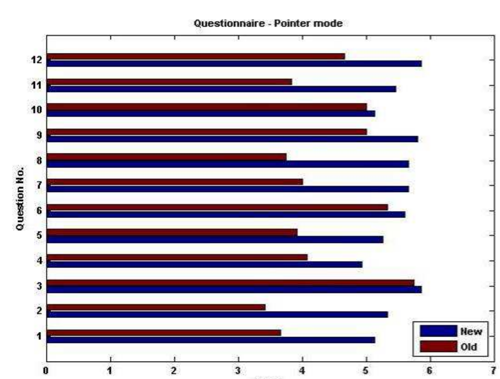

Fig. 15 – Comparison of questionnaire results for pointer mode

The red color bars in figures indicate results of the initial study while blue colored bars indicate results from current study. In the joystick mode number of questions have scores lower then in the initial study. This again could be attributed to high sensitivity due to which users had to execute numerous trajectory corrections while they found proposed visual feedback useful and enjoyable feature. At the same time pointer mode questionnaire scores were all higher (some considerably as depicted in Table 4) than in original study indicating (in our opinion) validity of applied improvements especially lowpass filtering and filter attenuation adjustment. Table 4 presents obtained difference in questionnaire marks for individual questions expressed in percentage of original study values and with green color indicating improvement.

Table 4 – Comparison of questioner results

Quest. No.	Diff. [%]			Quest. No.	Diff. [%]	
	J	P			J	P
1	+2.5	+38.9		7	-15.8	+41.8
2	+16.2	+55.8		8	-13.3	+51.2
3	+11.8	+2.1		9	+11.1	+16
4	+15.9	+20.8		10	-6.6	+2.6
5	+20.8	+34.4		11	-18.6	+42.8
6	+16.3	+5.1		12	-2	+25.7

P – Pointer mode; J – Joystick mode

It is worth nothing that we also experimented with different application scenarios for the proposed device. Investigated applications included typing using virtual keyboard and control of small 6 degree of freedom robotic manipulator. Initial results (not presented here) and user feedback are promising and justify further research.

5 Conclusions

The paper presents inertial sensor based (hands free) device for control of computer pointer and describes the improvements made since the first system version presented in [1]. It also proposes some alternative application scenarios for the device. The performance of the system was measured via throughput using multidirectional point-and-select task based on guidelines found in [25]. Obtained throughput results depended on the used control scheme and were 0.78 bits/s and 1.68 bits/s for joystick and pointer mode, respectively. The results are similar to ones obtained in our initial study, but the full impact of the proposed improvements is evident in comfort assessment via questioners. All of the participants found the device to be user friendly and easy to use/control with pointer mode being the preferred control technique. They reported no or low physical and mental effort, as well as low eye and neck fatigue. The presented results in our opinion justify implementation of the improvements and we expect some level of improvement in throughput values once the users become more accustomed to the system. It is worth noting that better performance (in terms of throughput) was achieved with only some of the improvements (i.e. low pass filtering with no sensitivity adjustment). This observation needs to be studied further. We also plan to lower sensitivity in joystick mode by means of lower movement resolution (e.g. 5^o in comparison to current 1^o resolution) and make some small adjustments to our visual feedback system which should result in better performance. Also, compensation of neutral head pose displacement introduced by lowpass filtering will be achieved by means of adjustable offset feature. Additional performance parameters proposed in [27] will be studied and applied since they might offer improved insight into device performance.

With all before mentioned improvements implemented we plan to measure system performance with the disabled subjects for whom the system is intended.

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