Open access • Proceedings Article • DOI:10.1109/EMBC.2015.7319370

Intuitive wireless control of a robotic arm for people living with an upper body disability — Source link

Cheikh Latyr Fall, Philippe Turgeon, Alexandre Campeau-Lecours, Véronique Maheu ...+5 more authors

Institutions: Laval University

Published on: 01 Aug 2015 - International Conference of the IEEE Engineering in Medicine and Biology Society

Topics: User interface, Wireless network interface controller, Robotic arm, Controller (computing) and Joystick

Intuitive Wireless Control of a Robotic Arm for people living with an upper body Disability

C. L. Fall, P. Turgeon, A. Campeau-Lecours, *Member, IEEE,* V. Maheu, M. Boukadoum, *Member, IEEE*, S. Roy, *Member, IEEE*, D. Massicotte, *Member, IEEE,* C. Gosselin, *Fellow, IEEE*, B. Gosselin, *Member, IEEE*

***Abstract*— Assistive Technologies (ATs) also called extrinsic enablers are useful tools for people living with various disabilities. The key points when designing such useful devices not only concern their intended goal, but also the most suitable human-machine interface (HMI) that should be provided to users. This paper describes the design of a highly intuitive wireless controller for people living with upper body disabilities with a residual or complete control of their neck and their shoulders. Tested with JACO, a six-degree-of-freedom (6-DOF) assistive robotic arm with 3 flexible fingers on its end-effector, the system described in this article is made of low-cost commercial off-the-shelf components and allows a full emulation of JACO's standard controller, a 3 axis joystick with 7 user buttons. To do so, three nine-degree-of-freedom (9-DOF) inertial measurement units (IMUs) are connected to a microcontroller and help measuring the user's head and shoulders position, using a complementary filter approach. The results are then transmitted to a base-station via a 2.4-GHz low-power wireless transceiver and interpreted by the control algorithm running on a PC host. A dedicated software interface allows the user to quickly calibrate the controller, and translates the information into suitable commands for JACO. The proposed controller is thoroughly described, from the electronic design to implemented algorithms and user interfaces. Its performance and future improvements are discussed as well.**

I. INTRODUCTION

The use of human-machine interfaces (HMI) for general purpose applications has seen tremendous growth in popularity during the past years. Movement tracking tools such as the Kinect [1], the Xsens devices [2] and the Leap Motion Controller [3] are good examples of powerful devices that can be used in a wide range of applications such as gaming, monitoring, computer control, etc. They are usually provided with software development kits (SDK) with which developers can add or implement their own functionalities. Using wearable body sensor networks (WBSN) as a means of measuring and tracking the motions of our body also confers interesting possibilities in terms of human-technology interfaces (Figure 1). Compared to the former movement tracking tools, WBSNs provide a wider range of applications due to limitations of cameras and infra-red sensors used in devices like the Kinect. The design of suitable human-technology interfaces for disabled people has often relied on mechanical tools such as head-mounted switches, dedicated keypads, trackballs, joysticks, sip-and-puff tools etc. Depending on the patients' disabilities, these devices could be sufficient and provide a good accuracy. For people suffering from more severe forms of disabilities, more ingenious and adequate controllers must be designed.

Fig. 1. Illustration of possible interactions between WBSNs and ATs such as the JACO arm.

JACO, depicted in Figure 1, is an assistive robotic manipulator commercialized by Kinova Robotics, Canada. Its vocation is to help people who have upper body disabilities in their daily activities. Mounted on the users' powered wheelchairs, its 6 degrees of freedom and the 3 flexible fingers of its end-effector are controllable via a sensitive joystick-based system which is adaptable to clients' abilities. Although current users reported real positive changes in their everyday life [4], using a WBSN-based system to control the robotic arm from the measured residual motions of patients would be a significant added value. This paper presents an intuitive wireless controller for assistive devices like the JACO arm, based on the natural motions of the upper body, and designed for people with severe disabilities, but with satisfactory residual control of their head and shoulders. Section II describes the methodology used to design such a controller, while section III provides details of its implementation. Section IV reports on the system's performance. Finally, sections V and VI conclude the article and provide an overview of the future work.

II. METHODOLOGY

People suffering from spinal cord injury have different degrees of autonomy depending on the damaged vertebrae [5]. Patients with injuries around the C5-C8 cervical vertebrae may have a weak residual control or total paralysis of their wrists, hands and fingers, while retaining complete control of muscles above the damaged areas. The use of controller devices such as joysticks is then tiring or almost impossible due to lack of dexterity. In such cases, WBSNs appear to be an adequate means of tracking and measuring

This work was supported, in part, by the Natural Sciences and Engineering Research Council of Canada, the Fonds de recherche du Québec - Nature et technologies and by the Microsystems Strategic Alliance of Quebec (ReSMiQ). C. L. Fall, P. Turgeon, and B. Gosselin are with the Dept. of Electrical and Computer Eng., C. Gosselin is with the Dept. of Mechanical Eng., Université Laval, Quebec, QC G1V 0A6, Canada (phone: +1(418) 656-2131; e-mail: cheikh-latyr.fall.1@ulaval.ca). A. Campeau-Lecours and V. Maheu are with Kinova, Canada, M. Boukadoum, S. Roy and D. Massicotte are with ReSMiQ.

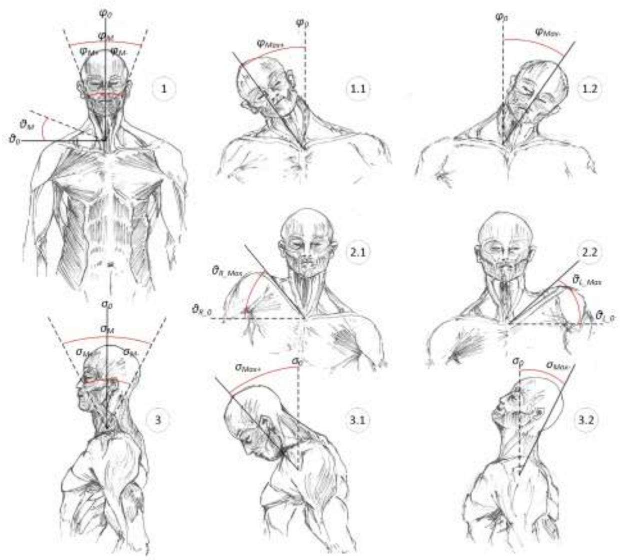

Fig. 2. Methodology used for the controller. Neutral positions (1 and 3) and control moves (1.1, 1.2, 2.1, 2.2, 3.1 and 3.2) are depicted

the residual gestures for further translation into adequate commands. The controller presented in this article has been designed for disabled people with Residual Functional Capacities (RFCs) allowing them to control muscles of their neck and shoulders. By simply moving their head in different directions and lifting their shoulders, patients are able to interact with assistive robotic devices using their natural gestures, and obtain the same results similar to those of a physical joystick controller. A related approach has been used in [6] where a head oriented wheelchair has been tested and revealed significant results. More recently, Mandel and colleagues [7] designed a 2-DOF head-joystick device, also for powered wheelchair control. To do so, the *Pitch* and *Roll* angles of the head are measured and translated into appropriate commands. Here, in addition to that, the controller we present reads the shoulders' elevation level as well, adding one more DOF compared to the controllers in [6] and [7]. Adequate light weight sensors have been designed to be worn with textiles and accessories such as glasses or hats (see Section III). Figure 2 provides a description of the control strategy. The 6 different control moves are illustrated, and the corresponding commands will be described in the next section.

III. DESIGN AND IMPLEMENTATION

The wireless controller (Figure 3) is built using off-the-shelf components and has been designed in such a way that miniaturized and low-power wireless nodes can ensure comfort and ease of use for users. This section describes each subsystem in detail and provides a description of the processing algorithms employed.

A. The inertial measurement unit (IMU) sensors

A large variety of sensors for physical activity measurement is commercially available. In [6], two 1-DOF IMUs have been used while in [7], a 9-DOF *XSens MTUx IMU* has been adopted. Such devices are essentially based on the use of accelerometers, gyroscopes and magnetometers. The LSM9DS0 multi-sensors module from *STMicroelectronics* was chosen for this project based on key

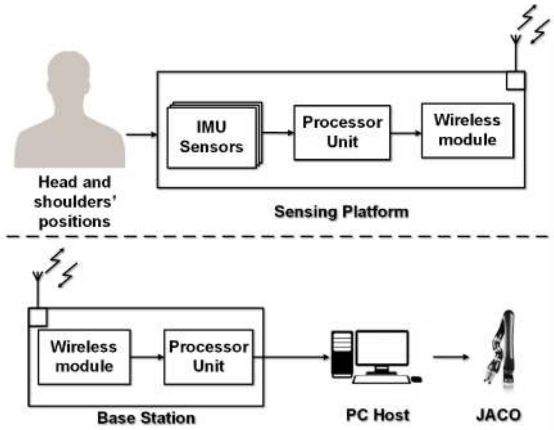

Fig. 3. Overview of the proposed wireless controller system

considerations such as power consumption, expected lifetime and low cost. It features a 16-bit architecture based on 9-DOF system in a package incorporating a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer for less than 20 mW of power-consumption. The sensor also incorporates an SPI controller which is used to communicate with a microcontroller unit (MCU). Its control registers are set such a way that the lowest output data rate (95 Hz) is selected given that it's a sufficient acquisition frequency for this application and the accelerometer's scale range is ± 2g. Three LSM9DS0 multi-sensor modules were required to support the control strategy presented in Figure 2: sensor S_1 measures the head position and sensors S_2 and S_3 are placed on the shoulders (see Figure 5). *Pitch* and *Roll* angles are computed using data gathered from accelerometers and gyroscopes. The next section describes the signal processing techniques employed as well as the controller's working principle.

B. Sensor's Data Processing Unit

The data processing is performed by the MCU. The MSP430F5529 development board from *Texas Instruments* is employed for this prototype due to its very low power consumption and the adequate processing capacity it confers.

Data Acquisition. The LSM9DS0 IMU module offers both I^2C and SPI interfaces. As mentioned above, the SPI interface is used to communicate with the MCU. The signal acquisition task is triggered using a timer, and is periodically called at every T=14ms to ensure a smooth interaction with the controlled robotic device. The obtained readings from the gyroscope and the accelerometer serve as inputs to the angle processing algorithm.

Angle Processing. A complementary filter [8] computes the *Pitch* and *Roll* angles from the obtained acceleration (accelerometer) and angular velocity (gyroscope) values as

$$\mathrm{pitch}_{n+1} = 0.98\left(\mathrm{pitch}_n + \int_0^T \dot{\emptyset}_{G\_z} dt\right) + 0.02\emptyset_{A\_pitch} \quad (1)$$

$$\mathrm{roll}_{n+1} = 0.98\left(\mathrm{roll}_n + \int_0^T \dot{\emptyset}_{G\_x} dt\right) + 0.02\emptyset_{A\_roll}, \quad (2)$$

where
$$\emptyset_{A\_pitch} = \tan^{-1}\left(\ddot{\emptyset}_{A\_z} / \ddot{\emptyset}_{A\_y}\right), \quad (3)$$

and
$$\emptyset_{A\_roll} = \tan^{-1}\left(\ddot{\emptyset}_{A\_x} / \ddot{\emptyset}_{A\_y}\right) \quad (4)$$

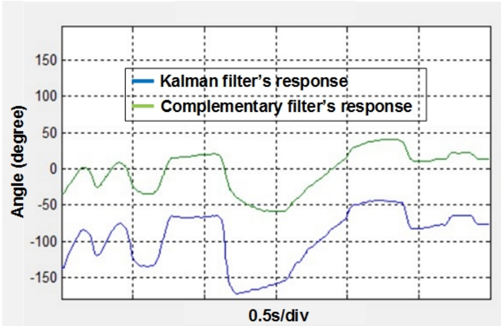

Fig. 3. Comparison between Complementary Filter (green) and Kalman Filter (blue) responses – results plotted with a 90 degree difference for clarity.

$\dot{\phi}_{G\_z}$ and $\dot{\phi}_{G\_y}$ are the angular velocity components on the x and y axis of the sensor, respectively, and $\ddot{\phi}_{A\_x}$, $\ddot{\phi}_{A\_y}$ and $\ddot{\phi}_{A\_z}$ are the acceleration components along x, y and z. Parameter T is the sampling period. No drift has been noticed during the tests which lasted approximately 30 minutes. Since the subjects' head and shoulders' inclination angles are limited, the solution we present only works for angles below 180°. Since using a Kalman filter would have been another alternative to obtain the correct angles from the IMU's measurement results [9], both algorithms have been implemented and the complementary filter option led to a considerable benefit in terms of computational resources, for output results close to those obtained with the Kalman filter (see Figure 3).

Mode selection. Assistive robotic devices such as JACO aim at reproducing natural motion of the human body. Here, dedicated user buttons allow the user to switch between different modes for translations along the x, y and z axis, arm and wrist rotations and the control of the fingers' positions. Only 3 of the 7 available user buttons are necessary to fully control the robotic arm using the joystick. These are implemented depending on patients' disabilities whether by using available user buttons on the MSP9430F5529 board, or by reading the 9 different possible combinations of head and shoulders positions and translating it into the right command. Thus, users can switch between the 3 different control modes as appropriate, and a visual feedback about the selected operating mode is provided by controlling two LEDs.

Data Transmission. As a means of communication between the sensor platform and its base station, the nRF24L01 wireless module, which is a 2Mbits/s low-power 2.4-GHz transceiver from *Nordic Semiconductor* is used in this design. Once the sensor node is in TX mode, the measurement results are transmitted to the base station using an 8-byte data format (1 start byte, 1 end byte, 4 angle values of one byte each, 1 information byte about the acquisition frequency, 1 byte for the operating mode selected), at a maximum frequency of 70 Hz. Communicating modules are set so that acknowledgments (ACKs), automatic retransmissions in case of fail and cyclic redundancy check (CRC) are enabled. The Enhanced ShockBurst baseband protocol engine embedded in the nRF24L01 package ensures a robust communication scheme. In addition, its "Multiceiver" solution that allows up to 6 simultaneous communications is a key enabler for the implementation of a wireless sensor network including several independent wireless nodes, leading to more precision and better ease of use for patients.

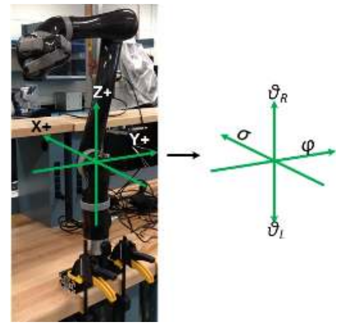

Fig. 4. Default mapping of measured angles following JACO's orientation from its home position.

C. Wireless Communication Link with the Base Station

As for the measurement platform, the base station consists of a MSP430F5529 development board connected to an nRF24L01 transceiver. The data transmitted by the sensor is transferred to a PC host through a serial link at a speed of 115,200 bps. Then, the data is interpreted and translated into adequate commands for controlling JACO.

D. The User Interface and the Control Algorithm

Since the implemented controller is tested using the JACO arm, the software interface had to be written in C++. In fact, JACO is provided with a dedicated Application Programming Interface (API) and libraries in C++ for research interest. Thus, the information about the head angles, the shoulders' levels and the operating modes are converted into the appropriate commands to control the robotic arm which is connected to the PC host through USB.

Assuming $Pitch_{Si}$ and $Roll_{Si}$ are *Pitch* and *Roll* angles measured from a sensor noted S_i, $Pitch_{S1}$, $Roll_{S1}$, $Pitch_{S2}$ and $Pitch_{S3}$ are the four angles measured by the wireless sensing platform and transmitted to the user interface via the base station. $Pitch_{S1}$ corresponds to the head inclination angle σ forward and backward, $Roll_{S1}$ gives the indication about the head inclination to the left and right sides φ, $Pitch_{S2}$ and $Pitch_{S3}$ are indicators of the right and left shoulders elevation ϑ_R and ϑ_L respectively. The default mapping is set so that σ and φ moves the robotic arm following the for-backward and left-right axis respectively, while ϑ_R and ϑ_L correspond to JACO's vertical displacements up and down, respectively (see Figure 4). A quick calibration step is necessary: the neutral positions (σ_0, φ_0, ϑ_R and ϑ_L), maximum for-backward head inclinations (σ_{Max+} and σ_{Max-}) and maximum right-left head angles (φ_{Max+} and φ_{Max-}), as well as maximum shoulders lifting angles (ϑ_{R_Max} and ϑ_{L_Max}) must be defined. As the given body positions may not be repeatable, and since head and shoulders can take slightly different neutral positions over time, margin angles (σ_{M+}, σ_{M-}, φ_{M+}, φ_{M+}, ϑ_{R_M} and ϑ_{L_M}) are defined as shown in Figure 2. Then, JACO's velocity or angular velocity is set to be proportional to the distance between the measured angle and the maximum calibrated value. This control method ensures a smooth and robust control of JACO, as described in the next section.

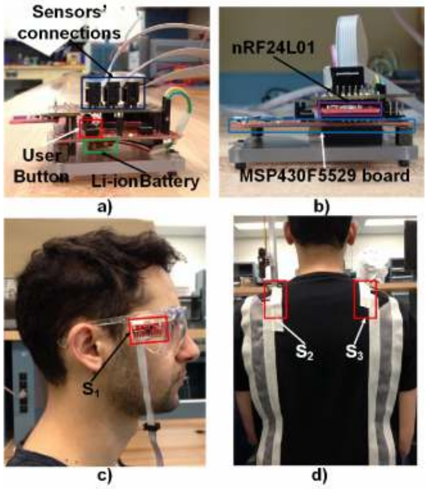

Fig. 5. The controller's sensing platform (a and b), and three IMU sensors located on the user (c and d).

IV. Measured Performance

The presented controller consists of a wireless sensing platform linked to a base station connected to a PC host on which a control algorithm in charge of translating angle values into the proper commands for JACO is running. The test prototype and sensors' placement on the user are depicted in Figure 5. A 3.7V 100-mAh small Li-ion rechargeable battery is used as a power source, which provides an autonomy of up to 105 min. The wireless communication link allows a 20 m reach. To assess the performance of the proposed wireless controller, it has been compared to JACO's joystick based system. To do so, 5 able-bodied subjects were asked to close drawers with the robotic arm controlled with the wireless controller at first, and then with the joystick controller. This task required at least 4 mode changes for which participants used buttons on the sensing platform, and the contribution of all the σ, φ, ϑ_R and ϑ_L angles (i.e. 6 DOFs). Although the two architectures are different, since the joystick is directly connected to the JACO arm and the wireless controller is connected to a PC host communicating through its API, the experimental results show that after a short training period of around 15 minutes, the participants were able to close the drawers in an average time of 23 s, starting from the home position of the robotic device. The same task is performed in 20 s using the joystick controller. These results stand as an experimental demonstration of how the proposed controller could be an interesting non-invasive alternative to classical human-machine interfaces for assistive devices such as JACO.

V. Discussion

Even though a wide range of human-technology interfaces are proposed today, a gap remains to be filled to ensure better comfort and ease of use to disabled people using assistive devices in their daily life activities. Like some other controllers [10], [11], the strength of the proposed controller lies on offering non-invasive, intuitive, wireless and wearable interfaces based on patients' RFCs. The employed control strategy assumes that the target users have residual control of their neck and shoulders, and a lack of dexterity in their fingers which prevents them from properly interacting with common interfaces such as joysticks. The proposed controller provides a good trade-off between performance and the number of necessary input signals. In future work, clinical tests will help quantifying the added value of such an assistive interface into the community of disabled people.

VI. Conclusion

In this paper, we presented a wearable intuitive wireless controller with up to 6 degrees of freedom, made from off-the-shelf components, and designed for upper body disabled people with residual control of their head position and also their shoulders. The controller enables the control of JACO, an assistive robotic arm. Preliminary test results have confirmed its ease of use and a performance close to that obtained with JACO's joystick based controller. In future work, miniaturization and system integration challenges will be addressed, and a complete wireless network including several independent wearable nodes will be designed and tested. Using dedicated low power architectures such as the system proposed in [12] to merge IMU sensors' information to patients' residual muscular activity in a smart way is also expected to further improve control performance.

References

[1] Yao-Jen Chang, Wen-Ying Han, and Yu-Chi Tsai. "A Kinect-Based Upper Limb Rehabilitation System to Assist People with Cerebral Palsy." In *Research in Developmental Disabilities* 34, no. 11, 3654–59, November 2013.

[2] Shuo Zhang, F. Naghdy, D. Stirling, M. Ros, and A. Gray. "Ankle Injury Assessment Using Inertial 3D Data." In *2013 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics (AIM)*, 810–15, 2013.

[3] D. Bassily, C. Georgoulas, J. Guettler, T. Linner, and T. Bock. "Intuitive and Adaptive Robotic Arm Manipulation Using the Leap Motion Controller." In *ISR/Robotik 2014; 41st International Symposium on Robotics; Proceedings of*, 1–7, 2014.

[4] V. Maheu, J. Frappier, P.S. Archambault, and F. Routhier. "Evaluation of the JACO Robotic Arm: Clinico-Economic Study for Powered Wheelchair Users with Upper-Extremity Disabilities." In *2011 IEEE Int. Conf. on Rehabilitation Robotics (ICORR)*, 1–5, 2011.

[5] A. W. Heinemann,"Spinal cord injury." In *Handbook of health and rehabilitation psychology,* 341-360, 1995, Springer US.

[6] C. Mandel, T. Rofer, and U. Frese. "Applying a 3DOF Orientation Tracker as a Human-Robot Interface for Autonomous Wheelchairs." In *IEEE 10th Int. Conference on Rehabilitation Robotics, 2007.*

[7] Y.-L. Chen, S.-C. Chen, W.-L. Chen, and J.-F. Lin. "A Head Orientated Wheelchair for People with Disabilities." *Disability and Rehabilitation* 25, no. 6 (January 1, 2003): 249–53.

[8] R.B. Widodo, H. Edayoshi, and C. Wada. "Complementary Filter for Orientation Estimation: Adaptive Gain Based on Dynamic Acceleration and Its Change." In *15th International Symposium on Soft Computing and Intelligent Systems (SCIS), 2014 Joint 7th Int. Conference on and Advanced Intelligent Systems (ISIS)*, 906–9, 2014.

[9] Gabriele Ligorio, and Angelo Maria Sabatini. "Extended Kalman Filter-Based Methods for Pose Estimation Using Visual, Inertial and Magnetic Sensors: Comparative Analysis and Performance Evaluation." *Sensors* 13, no. 2 (February 4, 2013): 1919–41.

[10] Hangue Park, M. Kiani, Hyung-Min Lee, Jeonghee Kim, J. Block, B. Gosselin, and M. Ghovanloo. "A Wireless Magnetoresistive Sensing System for an Intraoral Tongue-Computer Interface." In *IEEE Trans. on Biomedical Circuits and Systems* 6, no. 6, 571–85, December 2012.

[11] A.K. Tanwani, J. del R Millan, and A. Billard. "Rewards-Driven Control of Robot Arm by Decoding EEG Signals." In *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 1658–61, 2014.

[12] A. Yousefian, S. Roy, and B. Gosselin. "A Low-power wireless multi-channel surface EMG sensor with simplified ADPCM data compression." In *2013 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2287-90, 2013.