CLASSIFICATION OF HEAD MOVEMENT PATTERNS TO AID PATIENTS UNDERGOING HOME-BASED CERVICAL SPINE REHABILITATION

K. M. Vamsikrishna^{*}, Debi Prosad Dogra^{*}, Harish Bhaskar[†]

*School of Electrical Sciences, IIT Bhubaneswar, INDIA [†]Department of Electrical and Computer Engineering, Khalifa University, Abu Dhabi, U.A.E.

ABSTRACT

Physical rehabilitation under close supervision of experts is often recommended to patients suffering from cervical pain and join related injuries. However, complete supervised rehabilitation may not be possible due to various socioeconomical parameters. On the other hand, unsupervised rehabilitation may lead to post-injury complications. In this paper, we propose a pattern classification based method to understand head movement that is necessary to recognize unusual patterns during cervical spine rehabilitation. The proposed system takes the help of Kalman filter to fuse data acquired through camera and motion sensors. Patterns of the fused signals represent head displacement during left-right and front-back movements with respect to the central axes parallel to coronal and sagittal planes. Normal and abnormal patterns of movements are thereby represented using time series data that describes temporal change in the angle of head on above planes. Experimental validation has been done with data collected from several users. It has been observed that, our proposed methodology can precisely detect and represent abnormalities in head movements during cervical spine rehabilitation.

Index Terms— Head tracking, head-neck movement, cervical pain rehabilitation, pattern analysis, physical rehabilitation.

1. INTRODUCTION

Exercises involving head-neck movements in sagittal and coronal planes are typical recommendations for various physical rehabilitation including, cervical spine rehabilitation, vestibular rehabilitation, and neck-strain rehabilitation. Such rehabilitation exercises are important during the recovery [1], however, they require close supervision by experts [2, 3]. With growing demand across public health systems and the increase in overhead costs supporting rehabilitation procedures, there is compelling need to offer unsupervised rehabilitation. In recent years, it has become possible to exploit advances in visual and sensor technologies to offer selfguided systems and aiding tools to support both patients and experts for managing rehabilitation.

Alternative systems for rehabilitation, of both automatic



Fig. 1. (a) Depiction of head movement in left-right directions over the coronal plane. (b) Initial or resting projections of angles α_1 and α_2 on coronal plane.

and semi-automatic types, have engaged sensors such as cameras, inertial sensors, depth sensors. A typical example of one such system is proposed by in [4] for upper extremity stroke rehabilitation. Other systems, also popularly referred to as serious game based systems, whose objective is to provide a self-guided cure for neurological disorders through a gaming interface, have received considerable attention of the researchers. For example, the authors of [5] have proposed a system for chronic pain rehabilitation within a framework of serious gaming approach. Similarly, in [6], authors have proposed a vision based method to estimate the relative position of the head and shoulder for neurological practices. Cervical spine and head-neck systems, being more sophisticated, require a scientific model representing their mutual relationship to assure patients a comprehensive experience. Existing setup such as the representative kinematic model proposed in [7] to understand head movement w.r.t to cervical joint, is well known amongst health-care community. However, simultaneous measurements in coronal as well as sagittal planes, must be accomplished to make the system robust against various types of errors.

Alternatively, orthopedic Goniometers can be used for recording rapid measurements of angles. However, its use for the present context is limited. Thus, efforts are being made to develop other alternatives for accurately measuring head rotation. For example, [8] and [9] have presented several apparatus comprising of multiple digital camera to record images of human head that has been land-marked using several key-points. Very recently, the authors of [10] have proposed a system combining two cameras and a gyroscope, where the rotation angle of head and angle of inclination of shoulder, are computed by tracking the positions of infrared LEDs placed on the helmet and shoulders, respectively. Given that, existing systems use complex and expensive sensors, unsupervised rehabilitation seems more complicated, thus, requires intervention of field experts to make such systems operational.

The objective of this paper is to propose a low-cost, pattern analysis based simple yet effective methodology to precisely measure relative change in Euler angle across coronal as well as sagittal planes corresponding to left-right and frontback head movements. Our approach requires the following apparatus consisting with a low-cost web camera and IMU sensor in order to determine head rotation. As compared to the method proposed in [10], our proposed system does not require additional equipment such as helmets to landmark feature points. Use of complimentary sensors allow us coping with mutual inadequacies, thus, guaranteeing accurate and robust measurements. In this specific case, the measurement from the IMU sensor compensates for visual tracking errors during changes in illumination and abrupt motion. In addition to that, use of the visual sensor in conjunction with other sensors, offer necessary interactivity to the patient and the expert during pre and post rehabilitation procedure. Features for head movement detection can be extracted by tracking multiple key-points over the face and are fused with IMU sensor data to obtain correct trajectory of the head. Next, relative position of the head is measured using Euler angle over time. Features are fused using Kalman filter to estimate variations. A projection of the angle on a 2D plane is obtained. Finally, the fused signal is analyzed to detect variations in movement patterns.

Rest of the paper is organized as follows. In section 2, we present the methodology of the proposed pattern classification based system. Section 3 presents the results obtained using data recorded during the rehabilitation setup used by several volunteers. In section 4, we present the conclusion by mentioning some of the possible future extensions of the present work.

2. PROPOSED METHODOLOGY

Cervical spine rehabilitation procedure requires carrying out exercises involving head-neck movements under the close observation of experts. In order to illustrate a typical example of such an exercise involving head-neck movement over the coronal plane, Fig. 1 can be understood; where angles α_1 and α_2 vary during the course of head movement to facilitate cervical spine rehabilitation. Measurement of such angle variations are necessary for determining the head pose during rehabilitation. One of the Euler angles, e.g. ϕ , θ , or ψ having maximum variance can be used to represent the movement in either coronal or sagittal plane, depending upon the



Fig. 2. A typical hardware setup used for recording video and IMU sensor data is shown. (a) Side view. (b) Frontal view.

type of movement. One unit of web-camera and IMU sensor has been used to record parameters describing head-neck movement independently. next, a Kalman filter based fusion algorithm is applied to obtain the smoothed trajectory of the head.

2.1. System Design and Architecture

The purpose of the proposed design is to provide a low-cost yet reliable system to help patients and experts for managing cervical spine rehabilitation. In our proposed system, we have used the integrated camera available on laptops. The computer is placed in front of the patient at a reasonable distance such that a clear visual of the frontal face can be obtained. We have used Shadow Motion Capture Device enabled IMU sensor for recording head movement that allows readings the sensor remotely through its wireless interface. Both hardware have been synchronized programmatically. A homogeneous background is maintained during data collection to ensure less errors since vision-based systems are prone to such types of errors. The IMU sensor is attached on the head such that its direction of Z-axis becomes normal to the coronal plane. A typical hardware setup that has been used during data collection, is presented in Fig. 2.

2.2. Vision-based Head Tracking

Computer vision-based head tracking is described in this section. Using a setup as described in the preceding section, video sequences containing head movement during cervical spine rehabilitation, are recorded. Visual tracking of the head is done with the help of KLT based object tracker. Initially, the subject is made to align his / her head into an upright position facing the camera and we manually mark the center of head on the first frame. Further, a $w \times h$ sized rectangular window is created around the marked point of the patient's head. In the next step, a series of uniformly spaced k number of key-points are selected inside the window area. Let this set of points be represented using (1)

$$S = \{s_1, s_2, s_3, \dots, s_k\}.$$
 (1)

KLT tracker is then used to track these key-points as the subject goes for rehabilitation exercises. Next, relative angular change at each key-point location is determined by computing the deviation from the initial position. Angles are measured w.r.t a fixed reference point depending upon the plane on which head is being moved. Finally, the angular displacement of the head over time t is obtained using (2),

$$\dot{\alpha}^{t} = \frac{1}{k} \sum_{j=1}^{k} \tan^{-1}(\frac{M_{j} - m_{j}}{1 + M_{j}m_{j}})$$
 (2)

where,

$$M_j = \frac{y_{ref} - y_0}{x_{ref} - x_0}$$
(3)

and

$$m_j = \frac{y_{ref} - y_j}{x_{ref} - x_j} \tag{4}$$

 $(x_{ref}, y_{ref}), (x_0, y_0), \text{ and } s_j = (x_j, y_j)$ represent location of the reference point, starting and present locations of the j^{th} point, respectively. The reference point is selected around the chest of the patient to analyze movements on coronal plane. Reference point to analyze movements on sagittal plane is taken as a point on the line passing through the coronal plane.

2.3. Modeling Head Movement with the Inertial Sensor

Euler angle representing the position and orientation of the head w.r.t the inertial frame of reference can be computed from the raw data recorded through sensors (gyroscope, accelerometer, and magnetometer) incorporated inside IMU device. Let p, q, and r represent the gyro outputs according to the body-frame along three different axes of the coordinate system, respectively. Then, rate of change of Euler angle can be measured using (5) with the help of (6),

$$\begin{pmatrix} \dot{\phi} \\ \theta \\ \dot{\psi} \end{pmatrix}^t = D(\phi, \theta, \psi)^t \times \begin{pmatrix} p \\ q \\ r \end{pmatrix}^t$$
(5)

$$D(\phi, \theta, \psi)^t = \begin{bmatrix} 1 & \sin(\phi) \tan(\theta) & \cos(\phi) \tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)/\cos(\theta) & \cos(\phi)/\cos(\theta) \end{bmatrix}$$
(6)

such that, ϕ , θ , and ψ represent roll, pitch and yaw w.r.t the body centered coordinate system. Euler angle representing the orientation of head at a given time is fused with the visionbased observation to obtain a smoothed trajectory.

2.4. Sensor Fusion and Event Recognition

Computer vision-based tracking is often prone to errors that occur due to (mis)alignment, sudden variation in illumination, and abrupt motion of the target. Given that, the proposed system produces complementary tracking information of the head using the inertial sensors, it is possible to fuse these measurements together such that probability of tracking error can be reduced. In this context, we have adopted a data fusing methodology to fuse α and (ϕ, θ, ψ) recorded parallely through camera-based signal and inertial sensor-based

Table 1. Description of the dataset used in our experiments

	1			1
usor #	normal speed	slow speed	normal speed	normal speed
usei #	$< C_1, S_1 >$	$< C_1, S_1 >$	$< C_2, S_2 >$	$< C_3, S_3 >$
1	< 10,10 >	< 10,10 >	< 5,5 >	< 4,4 >
2	< 10,9 >	< 10,9>	< 6,5 >	< 5,5 >
3	< 7,8 >	< 8,10 >	$< 4,\! 6 >$	< 4,4 >
4	< 10,10 >	< 10,10 >	< 5,6 >	< 6,5 >
5	< 10,11 >	< 9,10 >	< 5,6 >	< 6,6 >

Note: C_1 -Extreme left to extreme right (coronal plane); S_1 -Extreme up to extreme down (sagittal plane); C_2 -Extreme left to partial right (coronal plane); S_2 -Extreme up to partial down (sagittal plane); C_3 -Partial left to extreme right (coronal plane); S_3 -Partial up to extreme down (sagittal plane);

signal. This has been done to obtain a smoothed trajectory of the head that can be used for extracting various parameters related to cervical spine rehabilitation. Sensor fusion can be implemented in several different ways. For example, Central Limit Theorem can be applied to get a smoothed resultant version of the signals with known variances. Another alternative is the use of Kalman filter to fuse the observations coming out of noisy measurements with different variances as described in the work of [11]. In this paper, the later approach has been adopted since it provides better approximation. Thus, complimentary observations, say x_1 and x_2 , obtained from two noisy processes with variances σ_1 and σ_2 , are fused using Kalman filter. Assuming the data is produced from a first-order system such that, P_k denotes the solution of the filter's equation, gain of the system cam be calculated using (7).

$$K_{k} = \begin{bmatrix} \frac{\sigma_{2}^{2}P_{k}}{\sigma_{1}^{2}P_{k} + \sigma_{2}^{2}P_{k} + \sigma_{1}^{2}\sigma_{2}^{2}} & \frac{\sigma_{1}^{2}P_{k}}{\sigma_{1}^{2}P_{k} + \sigma_{2}^{2}P_{k} + \sigma_{1}^{2}\sigma_{2}^{2}} \end{bmatrix}$$
(7)

It may be observed from above equation that, when the first measurement is noiseless, the filter ignores the second measurement and vice-verse. Therefore, the combined estimate is a weighted quantity of the quality of independent measurements.

3. RESULTS

In this section, the experimental results obtained using several test sequences recorded in a laboratory environment, are presented. The setup as depicted in Fig. 2 has been used to record measurements of vision as well as IMU sensors. Five volunteers within the age group of 21-30 participated in our experiments. Volunteers were asked to perform a set of predefined exercises involving head movements. These exercises were chosen after due discussions with the physicians, such that, they closely match with the requirement of cervical spine rehabilitation. These exercises are categorized into (i) extreme left to extreme right (ii) extreme up to extreme down (iii) extreme left to partial right (iv) extreme right to partial left (v) extreme up to partial down and (vi) extreme down to partial left. In Table 1, we present a summary of the dataset used in our analysis process. Experiments were carried out at normal as well as slow speeds. C_1 and S_1 represent scenarios demonstrated by participants with no abnormality w.r.t both

Table 2. Experimental results using C_1 and S_1 setup, NS: normal speed, SS: slow speed

User	A+ (NS)	A- (NS)	ρ (NS)	A+ (SS)	A- (SS)	ρ (SS)
	$C_1 S_1$					
1	$09.9\ 04.4$	$05.8\ 04.1$	$01.7\ 01.0$	$05.8\ 03.8$	$05.5\ 04.2$	01.0 00.9
2	21.304.9	$12.5\ 06.2$	$01.7\ 00.8$	$04.4\ 03.8$	$05.1\ 03.7$	$00.9\ 01.0$
3	$20.5\ 04.7$	$18.2\ 05.8$	$01.1\ 00.8$	$09.0\ 07.2$	$07.8\ 06.1$	$01.2\ 01.2$
4	$07.8\ 04.0$	$06.5\ 03.7$	$01.2\ 01.0$	$04.7\ 01.9$	$06.4\ 02.4$	$00.7\ 00.8$
5	00 7 02 6	12 4 02 8	00 8 01 2	05 0 02 6	04 5 02 4	01 2 01 5

Table 3. Experimental results using C_2 , S_2 , C_3 , and S_3 , NS: normal speed

User	A+ (NS)	A- (NS)	ρ (NS)	A+ (NS)	A- (NS)	ρ (NS)
	$C_2 S_2$	$C_2 S_2$	$C_2 S_2$	$C_{3} S_{3}$	$C_{3} S_{3}$	$C_{3} S_{3}$
1	$11.3\ 05.1$	$04.5\ 01.3$	$02.5\ 03.5$	$02.1\ 01.1$	$09.5\ 04.6$	$00.2\ 00.2$
2	$03.1\ 04.5$	$01.4\ 00.7$	$05.8\ 06.2$	$01.4\ 01.5$	$07.2\ 06.7$	$00.2\ 00.2$
3	$10.0\ 06.1$	$01.9\ 01.5$	$05.1\ 04.0$	$03.7\ 01.3$	$11.2\ 05.9$	$00.3\ 00.2$
4	$07.8\ 04.1$	$01.6\ 01.2$	$04.8\ 03.4$	$01.7\ 01.5$	$04.9\ 06.7$	$00.3\ 00.3$
5	$09.6\ 11.2$	$01.7\ 02.1$	$05.5\ 05.3$	$01.4\ 01.7$	08.1 09.4	$00.2\ 00.2$

planes. On the other hand, C_2 , S_2 , C_3 , and S_3 represent four possible types of abnormalities. Each of these movement was performed multiple times by every participant. The table also indicates the value representing the number of times a particular movement was performed by a participant.

We have computed following statistics to understand the process of cervical spine rehabilitation. Given a fused signal, say z(t), area under the curve between two successive zero crossing is estimated and denoted by A_{+} and A_{-} , where they represent amount of variation in angle during left (coronal) or upward (sagittal) and right (coronal) or down (sagittal) movements, respectively. Further, $\rho = \frac{A_+}{A_-}$ is defined as an indicator of the symmetry in movement. Using normal-speed cycles for every participant, ρ_{avg} is estimated and used for identifying left, right, up or down abnormality. In Figs. 3-5, graphical representations of three possible scenarios are depicted. Measurements were obtained using camera as well as IMU sensors and the fused signals are presented. It can be verified from the figures, independent measurements using visual system or IMU sensor, are quite satisfactory, particularly when signals are less noisy. However, if noisy measurements are obtained from one sensor, as shown in Fig. 5, where the vision-based measurements are by artifacts, accurate approximation can be obtained through sensor fusion. Therefore, the proposed fusion-based technique has been found to be reliable over independent analysis in the present context.

Tables 2-3 summarize the experimental results. It can be



Fig. 3. Demonstration of normal-speed head movement when a subject has no abnormality (a) Camera measurement (b) IMU measurement (c) Fused Measurement.



Fig. 4. Demonstration of normal-speed head movement when a subject has abnormality (a) Camera measurement (b) IMU measurement (c) Fused Measurement.



Fig. 5. Noisy measurements using camera during normalspeed head movement (a) Camera measurement (b) IMU measurement (c) Fused Measurement.

observed that, the value of ρ does not vary much during entire experiment and its value becomes close to 1 for normal participants carrying no injury. However, if a person with some level of abnormality (either in coronal or sagittal plane) performs head movement, ρ deviates significantly. For example, in case of C_2 and S_2 types of abnormalities, $\rho >> 1$ since the denominator (A_-) becomes reasonably small as compared to the numerator (A_+). Conversely, when C_3 , and S_3 category movements occur, the value of ρ becomes much lesser than 1. It has been verified that, ρ can be a good indicator of abnormality type that may be used to quantify the extent of abnormality using suitable thresholds.

4. CONCLUSION

The paper proposes a low-cost multi-sensor fusion based technique to facilitate unsupervised cervical spine rehabilitation. A combination of camera and IMU sensor-based apparatus has been used to record head-neck movements during cervical spine rehabilitation. Noisy measurements recorded using these sensors are fused using a Kalman filter based prediction technique and the resultant signal is processed to extract valuable information about the rehabilitation process, including the identification of abnormalities. Several extensions of the present work are possible including, processing of the fused signal to extract features such as skewness, abrupt changes, and periodicity to provide deeper analysis of the abnormality.

5. REFERENCES

- M. Williams and R. Kirsch, "Evaluation of head orientation and neck muscle emg signals as command inputs to a human computer interface for individuals with high tetraplegia," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 16, no. 5, pp. 485– 496, Oct 2008.
- [2] M. Lee, M. Wong, F. Tang, W. Chang, and Y. Chen, "Cervical traction using emg biofeedback," *IEEE Engineering in Medicine and Biology Magazine*, vol. 15, no. 3, pp. 83–87, May 1996.
- [3] J. Williams and T. Belytschko, "A dynamic model of the cervical spine and head," *Final Technical Report*, *Northwestern Univ Evanston IL*, 1981.
- [4] L. Sucar, R. Luis, R. Leder, J. Hernandez, and I. Sanchez, "Gesture therapy: A vision-based system for upper extremity stroke rehabilitation," in *Engineering in Medicine and Biology Society, Proceedings of the Annual International Conference of the IEEE*, Aug 2010, pp. 3690–3693.
- [5] S. Christian, P. Thomas, K. Hannes, J. Stephanie, and V. Miriam, "Chronic pain rehabilitation with a serious game using multimodal input," in *Virtual Rehabilitation, Proceedings of the International Conference on*, June 2011, pp. 1–8.
- [6] Y. Song, Y. Luo, and J. Lin, "Detection of movements of head and mouth to provide computer access for disabled," in *Technologies and Applications of Artificial Intelligence, Proceedings of the International Conference on*, Nov 2011, pp. 223–226.
- [7] M. Ouerfelli, V. Kumar, and W. Harwin, "Kinematic modeling of head-neck movements," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 29, no. 6, pp. 604–615, Nov 1999.
- [8] J. Hozman, D. Sturm, and J. Stoklasa, "Measurement of head position in neurological practice," in *Biomedical Engineering, Proceedings of the*, 2004, pp. 586–589.
- [9] J. Charfreitag, J. Hozman, and R. Cerny, "Measurement of eye and head position in neurological practice," in World Congress on Medical Physics and Biomedical Engineering, Proceedings of the, 2009, pp. 57–60.
- [10] P. Kutilek, J. Charfreitag, and J. Hozman, "Comparison of methods of measurement of head position in neurological practice," in XII Mediterranean Conference on Medical and Biological Engineering and Computing, Proceedings of the, 2010, vol. 29, pp. 455–458.

[11] J. Sasiadek and P. Hartana, "Sensor data fusion using kalman filter," in *Information Fusion, Proceedings of the 3rd International Conference on*, July 2000, vol. 2, pp. 19–25.