A Robust Interface for Head Motion based Control of a Robot Arm using MARG and Visual Sensors

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***Abstract*—Head-controlled human machine interfaces have gained popularity over the past years, especially in the restoration of the autonomy of severely disabled people, like tetraplegics. These interfaces need to be reliable and robust regarding the environmental conditions to guarantee safety of the user and enable a direct interaction between a human and a machine. This paper presents a hybrid MARG and visual sensor system for head orientation estimation which is in this case used to teleoperate a robotic arm. The system contains a Magnetic Angular Rate Gravity (MARG)-sensor and a Tobii eye tracker 4C. A MARG sensor consists of tri-axis accelerometer, gyroscope as well as a magnetometer which enable a complete measurement of orientation relative to the direction of gravity and magnetic field of the earth. The tri-axis magnetometer is sensitive to external magnetic fields which result in incorrect orientation estimation from the sensor fusion process. In this work the Tobii eye tracker 4C is used to increase head orientation estimation because it also features head tracking even though it is commonly used for eye tracking. This type of visual sensor does not suffer magnetic drift. However, it computes orientation data only, if a user is detectable. Within this work a state machine is presented which enables data fusion of the MARG and visual sensor to improve orientation estimation. The fusion of the orientation data of MARG and visual sensors enables a robust interface, which is immune against external magnetic fields. Therefore, it increases the safety of the human machine interaction.**

***Index Terms*—sensor fusion, orientation, hybrid sensor system, Kalman filter, state machine, magnetic immune**

I. Introduction

Direct interaction of a human with assistive technologies, e.g. robots, is typically achieved via interfaces. Usually, these interfaces operate using the hands of a human. However, in cases where the hands are occupied or cannot be used due to disabilities, e.g. tetraplegia, new handsfree interfaces have been proposed, e.g. gaze based interfaces [1] or conductive elastomer garments [2]. A promising handsfree interface focuses on head motion measurement through MARG-sensors and offers a three-dimensional control of a robot [3] [4]. These types of sensors consist of tri-axis accelerometer, gyroscope and magnetometer and can be used to estimate orientation in three-dimensional space. Head motion as well as gestures of a human are measured through MARG sensors and mapped onto a robot.

The requirement to guarantee safety and robustness of this type of interfaces is related to drift free head orientation measurement. This is achieved through the algorithm of sensor data fusion as well as calibration of the different types of sensors. While tri-axis magnetometer and accelerometer sensors provide an absolute reference for orientation by measurement of earth's gravity and magnetic field, calibration and sensor data fusion is of most importance. With an absolute reference it is possible to compensate for orientation drift induced by the gyroscope. However, if the MARG sensor is exposed to magnetic disturbance, i.e. hard or soft iron effects [5], the reference related to the magnetic field is no longer stable. This results in drift of the heading estimate, known as yaw angle. Another source or algorithm for a stable reference is needed [6]. In the case of short term magnetic disturbance ($\leq 30\ s$), this problem can be compensated through sensor data fusion algorithms [7] [8]. If the magnetic disturbance persists or the surrounding field changes completely, the sensor has to be recalibrated. Magnetometer calibration is usually done by waving the device in three dimensional space to sample magnetic field values and map them onto a unit sphere [9].

This is not practical nor possible if the sensor is used as a hands-free interface to control a robotic arm. A growing error due to magnetic disturbance could be interpreted as a control input to the robot. This might result in unwanted movement of the robot and cause harm or injury. Within this paper a hybrid MARG-visual interface for the control of a robotic arm is presented. The interface is immune against magnetic disturbance and therefore does not need to be recalibrated. This increases the safety in a direct interaction with a robot.

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A. Related Work

In [3] Rudigkeit et al. presented a novel head motion based interface for direct control of a robotic arm. Head motion is recorded using MARG sensors and orientation is presented as Euler angles in order to have three independent signals to control the robot. Furthermore a control structure was introduced which maps the three degrees of freedom (DOF) from head motion to the seven DOF from the robotic arm. The different DOFs were divided into subgroups which could be chosen by the user. Switching between the subgroups is performed through well-defined head movement. This interface was further improved by gesture based recognition from Jackowski et al. [4].

In [8] we introduced a robust sensor fusion algorithm that calculates orientation as quaternion using a linear Kalman filter which incorporates a gradient descent algorithm and is capable of overcoming short term magnetic distortion. This is achieved by switching between Inertial Measurement Unit (IMU) and MARG equations inside the gradient descent filter stage depending on a magnetic disturbance threshold. The switching is based on large innovation method to detect outliers.

This paper presents a robust interface for head motion based control of a robot arm using a hybrid system consisting of MARG and visual sensors. We measure a user's head orientation through MARG and visual sensor. MARG sensor orientation is computed through the robust linear Kalman filter and is fused with the orientation data from the visual tracking system (Tobii eye tracker 4C). The data fusion process is accomplished inside a finite state machine. By fusing the orientation data of both systems, magnetic disturbances regarding the heading estimate are eliminated. Furthermore, the system can be used without magnetometer calibration or reference while the user is in the visual field of the camera.

II. ROBUST ORIENTATION ESTIMATION

Within this work it is proposed to fuse 3D orientation estimation from a MARG sensor with visual orientation estimation to form a robust and magnetic immune head motion based control for a robotic arm. Fig. 1 shows the concept. Measurement data from the MARG sensor are processed by MARG-/IMU sensor fusion algorithm (given in subsection A) and visual data is processed by the Tobii Streaming engine (given in subsection B). The fusion state machine describes the computation of the final orientation denoted ${}^{N}_{B}\mathbf{q}_{final}$. The states, inital state and transition conditions are defined in subsection C.

A. Orientation estimation from MARG sensor

As proposed in [8] we estimate orientation based on the fusion of two quaternions inside a linear Kalman filter. A quaternion is a four dimensional representation of orientation. Quaternions do not suffer gimbal-lock which is associated with Euler angle representation. The method we proposed in [8] relies on a gradient descent algorithm (GDA) for orientation measurement developed by Madgwick et al. [10].

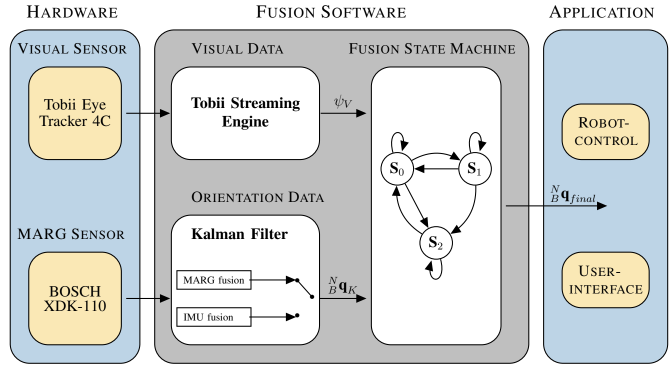

Fig. 1. General concept of the proposed fusion method.

We use the GDA to compute a measurement quaternion either through magnetometer and accelerometer (MARG case) or accelerometer only data (IMU case). The gyroscope data are used in the prediction step of a linear Kalman filter (KFF), while the measurement coming from the GDA is used in the update step to correct for gyroscope bias drift. Inside the filter, we use a large innovation criterion to detect outliers in the magnetometer data. Upon detecting large differences, we switch from MARG to IMU case equations inside the GDA. This eliminates the effect of magnetic disturbance on the heading estimate from the measurement quaternion. If the disturbance vanishes, the GDA filter stage will fall back to the MARG case. The threshold that determines the switching from MARG to IMU case is termed ϵ_m and is based on experimental results to guarantee best switching capabilities when subject to magnetic disturbance [8].

This method enables a robust orientation estimation expressed as quaternion but is limited to short term magnetic disturbances. This is due to the gyroscope bias regarding the heading estimate which will result in large drift if not corrected through another source of reference. Fig. 2 gives an overview of the filter and its dependencies. The entire mathematical derivation of the filter can be found in [8].

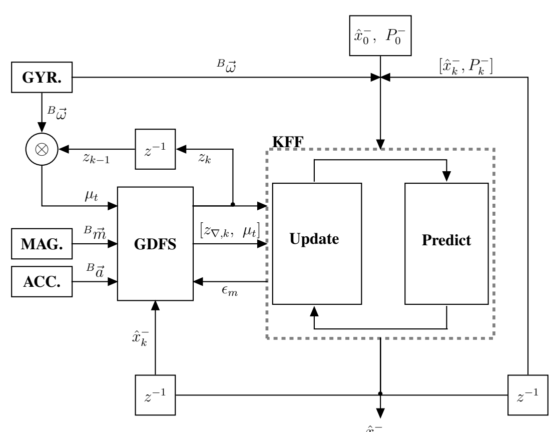

Fig. 2. Diagram of both filter stages, the Kalman filter framework (KFF) and the gradient descent filter stage (GDFS), and their interconnections [8].

B. Orientation estimation from visual sensor

Visual orientation data is retrieved from the Tobii eye tracker 4C[1]. This device is capable of eye tracking as well as head tracking [11]. It is an innovative product in the consumer market and is mainly used for video game augmentation. The head orientation data of a user in front of the eye tracker can be retrieved through the Tobii streaming engine [12]. It is set as ground truth regarding head orientation in this application. The Tobii streaming engine gives orientation as Euler angles rather than quaternions. This is convenient for the proposed work because we only use the yaw angle from the Tobii eye tracker as a heading drift correction source when magnetic disturbance is present. We directly calculate a correction quaternion based on the difference from MARG and eye tracker yaw angles. The computation of the correction quaternion is subject to the following subsection C.

Other visual sensors might be used as well, for example the Microsoft Kinect [13], but the Tobii 4C also features eye tracking which will be used in a future multimodal interface.

C. Fusing MARG and visual orientation data

State machines have shown to deliver good results regarding the fusion of MARG and visual sensors [14]. Orientation data from MARG sensor measurements is computed via the Kalman filter framework described in section II, A. Within this work, the detection of magnetic disturbance inside the Kalman filter will be used to include the visual orientation data from the Tobii eye tracker 4C and fuse it with the measurement vector of the Kalman filter. If the MARG sensor is subject to magnetic disturbance, it will switch from MARG to IMU like data fusion and include visual orientation estimation to compute a correction quaternion. A finite state machine is used to control the fusion process. The transition conditions are related to the change from non magnetic- to magnetic deviation and valid- to non valid visual data.

1) Correction Quaternion: Since both systems calculate orientation in different reference frames a transformation into one common reference frame is required to compute a final fused orientation. We choose the camera reference frame to be the global orientation reference frame for our purpose. The transformation from MARG reference frame into the camera reference frame is achieved in the initial alignment step. Both sensors measure a user's head orientation. We then transform the MARG sensor orientation measurement into the camera reference frame by comparing rotations. When the eye tracker measures zero rotation, the MARG reference frame is transformed by quaternion multiplication

$$^N_B\mathbf{q}_0 = x_{k+1}^{-1} \bullet x_{k+1} \tag{1}$$

where the superscript ($^{-1}$) denotes the conjugate quaternion of the state vector x_{k+1} of the linear Kalman filter

$$x_{k+1}^{-1} = \begin{pmatrix} \mathbf{q}_1 & -\mathbf{q}_2 & -\mathbf{q}_3 & -\mathbf{q}_4 \end{pmatrix}^T \tag{2}$$

[1]https://tobiigaming.com/eye-tracker-4c/

and $^N_B\mathbf{q}_0$ is

$$\begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix}^T. \tag{3}$$

To achieve similar orientation computations, a scaling factor is computed that merges visual and MARG sensor orientation. The user rotates the head towards ± 30 degrees measured with the eye tracker. Based on the measurements, a linear scaling factor is computed and multiplied with the angles coming from the eye tracker.

A correction quaternion $^N_B\Delta\mathbf{q}_{corr}$ is formed from the yaw deviation (heading) between MARG- and visual sensor. Attitude in the form of pitch and roll angle is not affected by magnetic disturbance and is therefore set to zero when forming the correction quaternion. The simplified calculation of a quaternion from Euler angles results in

$$^N_B\Delta\mathbf{q}_{corr} = \begin{pmatrix} cos(\psi_{corr}/2) & 0 & 0 & sin(\psi_{corr}/2) \end{pmatrix}^T, \tag{4}$$

where ψ_{corr} represents the deviation between visual(ψ_V) and MARG (ψ_K) heading calculation

$$\psi_{corr} = \psi_K - \psi_V, \tag{5}$$

where ψ_K is the Euler angle representation from the quaternion x_{k+1} computed by the Kalman filter (see Fig. 2).

The correction quaternion is applied to the measurement quaternion from the GDA, when it is subject to long term magnetic deviation, which is detected through large innovation criterion from [8]. In such a case the Kalman filter switches the measurement equation towards the IMU equation. The calculated IMU measurement quaternion is directly corrected by the conjugated correction quaternion ($^N_B\Delta\mathbf{q}_{corr}$) through quaternion multiplication

$$^N_B\mathbf{q}_{\nabla,t} =^N_B \Delta\mathbf{q}_{corr}^{-1} \bullet {}^N_B\mathbf{q}_{\nabla,t}. \tag{6}$$

The corrected measurement quaternion is then used in the Kalman filter to compute a final orientation. This ensures a smooth data fusion even when large visual correction steps are applied and motion based weighting of the different sensors coming from the Kalman Filter algorithm from [8]. This means that during fast dynamic motion the final orientation is mainly composed of gyroscope orientation estimation whereas under slow or static motion final orientation is computed mainly based on the measurement quaternion.

2) State Machine: Two transition conditions are used to switch between three different states to generate robust and magnetically immune orientation data.

The first transition condition controls switching between the states MARG/IMU/visual orientation calculation and IMU/visual correction specified by S0 and S1 respectively (Fig. 3). The condition is generated by logical combination of Δm and Δd. Δm represents the recognition of magnetic disturbance through the Kalman filter. The difference between yaw angle (heading) calculated by MARG and visual sensors is denoted as Δd. The values are formed as follows

$$\Delta m = \begin{cases} 1, |y_k| \geq \epsilon_m \\ 0, |y_k| \leq \epsilon_m \end{cases} \tag{7}$$

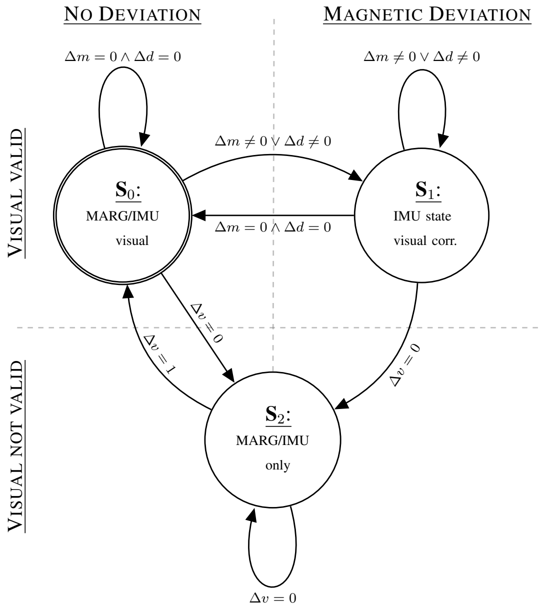

Fig. 3. State Machine SM $\{\Sigma, S_0, S_1, S_2, \delta\}$.

TABLE I
STATE TRANSITION TABLE

Condition(δ)		***Current State (S)***		
		$\mathbf{S}_0$	$\mathbf{S}_1$	$\mathbf{S}_2$
Δv=1		$\mathbf{S}_0$	-	-
Δv=0		$\mathbf{S}_2$	$\mathbf{S}_2$	$\mathbf{S}_2$
Δm	Δd			
$= 0$	$= 0$	$\mathbf{S}_0$	$\mathbf{S}_0$	-
$\neq 0$	$= 0$	$\mathbf{S}_1$	$\mathbf{S}_1$	-
$= 0$	$\neq 0$	$\mathbf{S}_1$	$\mathbf{S}_1$	-
$\neq 0$	$\neq 0$	$\mathbf{S}_1$	$\mathbf{S}_1$	-

where Δm is true when the norm of the innovation is larger than the magnetic disturbance threshold and

$$\Delta d = \begin{cases} 1, |\psi_{corr}| \geq c \\ 0, |\psi_{corr}| \leq c \end{cases} \tag{8}$$

where Δd is true when the difference between MARG and the visual system is larger than a constant angle c. This angle is determined in experiments to have a small difference between state transitions when the correction quaternion is applied.

The second condition Δv denotes visual valid data which is retrieved from the eye tracker. If the tracker fails to recognise orientation or a user moves too fast, Δv is set to zero. The fusion process in the different states is described below and depicted in Fig. 3. Depending on Δv the state machine changes between the states $\mathbf{S}_0$/$\mathbf{S}_1$ and $\mathbf{S}_2$. The common feature of states $\mathbf{S}_0$ and $\mathbf{S}_2$ is that MARG and IMU data are used. However, in the state $\mathbf{S}_2$ the visual data is not applicable.

Fig. 3 and Tab. I depict the state machine as well as the transition conditions.

The state machine starts in state $\mathbf{S}_0$ in which both visual and MARG orientation data are valid and no deviation occurs. The final orientation is calculated based on MARG orientation data only without the need for synchronization with visual orientation data.

$${}^N_B\mathbf{q}_{final} = {}^N_B\,\mathbf{q}_{S_0} = x_{k+1}. \tag{9}$$

The index $\mathbf{S}_0$ denotes that the final quaternion is only based on MARG equations from the Kalman filter.

If deviation between MARG and visual orientation occurs, the state machine switches from $\mathbf{S}_0$ to $\mathbf{S}_1$. In case the robust Kalman filter recognizes magnetic disturbance ($\Delta m \neq 0$) and the MARG heading data and visual heading data deviate ($\Delta d \neq 0$), magnetic disturbances are presumably the cause of the deviation. In this circumstance the final orientation will be calculated by fusing the IMU measurements quaternion from the Kalman filter with visual heading data through equations (4-6). The final orientation is

$${}^N_B\mathbf{q}_{final} = {}^N_B\,\mathbf{q}_{S_1} = x_{k+1}, \tag{10}$$

where the index S_1 denotes that the final quaternion is computed through MARG and visual sensor data fusion from section C equations (4) - (6). If the deviation vanishes, the orientation will be calculated through MARG only ($\mathbf{S}_0$).

The transition condition from state $\mathbf{S}_0$ to $\mathbf{S}_1$ is formed through a logical OR link of the Δm and Δd. This is due to gyro bias correction of the MARG sensor. As the visual sensor is not sensitive to magnetic field disturbances and if there is no deviation between MARG and visual orientation data ($\Delta d = 0$) the magnetic disturbance detection is expected to be zero as well ($\Delta m = 0$). However, if the Kalman filter estimates magnetic deviation ($\Delta m \neq 0$) this is caused through gyroscope bias drift due to temperature changes located at the MARG sensor chip. This deviation is also addressed by switching from state $\mathbf{S}_0$ to $\mathbf{S}_1$. To switch back towards $\mathbf{S}_0$, both values (Δm, Δd) have to be zero and are therefore connected via logical AND link.

A transition from state $\mathbf{S}_0$ or $\mathbf{S}_1$ to state $\mathbf{S}_2$ is given in case if visual orientation data is not valid ($\Delta v = 0$). Visual data are only valid if a user is present. The final orientation in state $\mathbf{S}_2$ is calculated by MARG sensor data fusion only. If magnetic disturbance is recognized ($\Delta m \neq 0$) and visual data are not valid the Kalman filter will switch towards the IMU equations resulting in a final orientation

$${}^N_B\mathbf{q}_{final} = {}^N_B\,\mathbf{q}_{S_2} = x_{k+1}, \tag{11}$$

where S_2 denotes orientation calculation from MARG or IMU equations only.

III. EXPERIMENTAL SETUP

The proposed fusion process was implemented using C++ on a 64 bit version of Windows 10. We used a MARG sensor from Bosch, the XDK 110 Cross-Domain Development Kit[2]. The XDK 110 features 16 bit tri-axis accelerometer, gyroscope as well as a magnetometer, an on-board 32-Bit microcontroller and wireless data transfer [15]. It was programmed to output raw values at 100 Hz, which are directly fed to the Kalman

[2]https://xdk.bosch-connectivity.com/

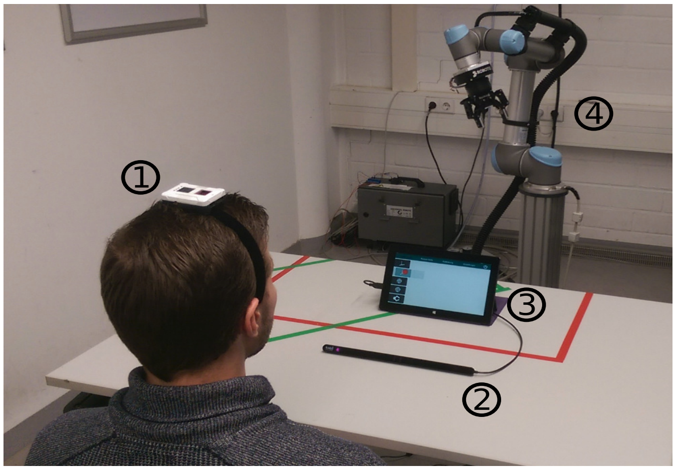

Fig. 4. Setup for the proposed hybrid MARG and visual interface. The user is seated in front of the Tobii eye tracker (2) while the XDK 110 (1) is placed on the user's head by a headband. Data from the hybrid system is fed to the computer (3) to calculate orientation and control a robotic arm (4, *UR5*).

filter. The sensor was calibrated in the surrounding magnetic field through the process described in [9]. Visual head orientation data were retrieved from the Tobii eye tracker 4C via the streaming engine. The data is directly fetched from the API when head rotations are valid and recognized. A second commercially available MARG sensor, the FSM9, was used to determine the correctness of orientation data. The robot (UR5) is controlled via ROS and based on the previous work from Rudigkeit et al. [3] and Jackowski et al. [4], where a single MARG-sensor is used to measure head orientation and control the robot. In this work the proposed system is used to get the head orientation data to control the robotic arm.

A user was seated in front of the eye tracker. The MARG-sensor (XDK-110) was attached to the top of a headband which the user had to wear. The constant deviation angle c was set to be $\pm 3°$. The user had to face the eye tracker and was instructed to rotate his head that the visual orientation data was zero for all angles. Upon reaching zero angles, the rotation quaternion was computed to transform the MARG orientation into the shared camera reference frame. After this alignment phase the user was instructed to perform various head motions. To compare both systems, we defined five yaw reference angles ($0°$,$\pm 15°$,and $\pm 30°$). The user had to rotate his head towards these reference angles marked by stripes and hold the head stationary for a minimum of five seconds. Two different subsets were conducted. Every set was recorded to evaluate performance for undistorted and magnetic distorted cases to investigate behaviour under long term magnetic disturbance. Magnetic disturbance was introduced by bringing an iron bar close to the sensor from different directions ($2\ cm$).

IV. Results

The performance of the proposed fusion method is presented in Euler angles and compared against orientation estimation from both MARG sensors, the FSM-9 with commercial data fusion, and the XDK-110 with the Kalman Filter proposed in [8]. The calculated Euler angles are divided into two subsets. Subset one compares the orientation of the heading or yaw angle respectively, estimated by the sensor fusion algorithms without magnetic disturbance. Subset two deals with the same data while magnetic disturbance is present for a long duration ($\gg 30\ s$). Three sensor fusion algorithm are tested (Fig. 5). The algorithm proposed within this work is given in blue, the commercial one in red and the algorithm proposed in our related work [8] in light blue.

The subset with no magnetic disturbance shows that all fusion methods compute similar orientations. The maximum offset per different fusion algorithm is around $\pm 2°$ from the baselines (see Fig. 5, left).

The right hand side of Fig. 5 shows typical results of yaw angle estimation when magnetic disturbance is present for more than $30\ s$. At startup, no disturbance is present and all fusion methods compute similar orientation. After $68\ s$, a ferromagnetic iron rod is brought close to the sensor resulting in magnetic disturbance. Both MARG-sensor fusion algorithms (related work algorithm [8] with XDK-110 and FSM-9 - MARG sensor with commercially available fusion algorithm) start diverging from the real orientation. At about $155\ s$, $87\ s$ after magnetic disturbance is introduced, the MARG only fusion methods (red and light blue lines) diverge far from the correct orientation computation. The commercially available algorithm from the FSM-9 peaks at $1°$, when it should be around $30°$ and the XDK 110 with related work [8] fusion algorithm results in $48°$ peak, whereas the proposed visual and MARG fusion method computes the expected value of $30°$ with a small deviation of $1°$. This is due to the visual yaw correction of the proposed sensor fusion algorithm at slow or stationary head movements, indicated by the plateaus from the blue line. However, the MARG only solutions drift during these steady state phases, which is indicated by rising or falling yaw angles. As can be seen, the XDK-110 with the filter from our related work [8] drifts continuously but follows the shape of motion. This is because of the threshold based switching coming from the large innovation detection, enabling the filter to compute an orientation without magnetometer reference. The proposed fusion method benefits from this algorithm. When visual data is not valid and magnetic disturbance is present the proposed fusion method will compute a similar error because of the switching capability of the Kalman filter. The commercial data fusion algorithm from the FSM-9 drifts towards the opposite direction of the head motion and has a similar shape (rising and falling edges) during dynamic motions.

V. Conclusion

The proposed MARG and visual fusion process enables a robust orientation estimation which is key to generate a safe human machine interaction, e.g. controlling a robotic arm. The proposed fusion method is capable of overcoming magnetic disturbances regardless of the duration of the disturbance, while visual head motion orientation is available. In the case where no visual information the proposed fusion method relies on MARG orientation estimation from [8] only. The

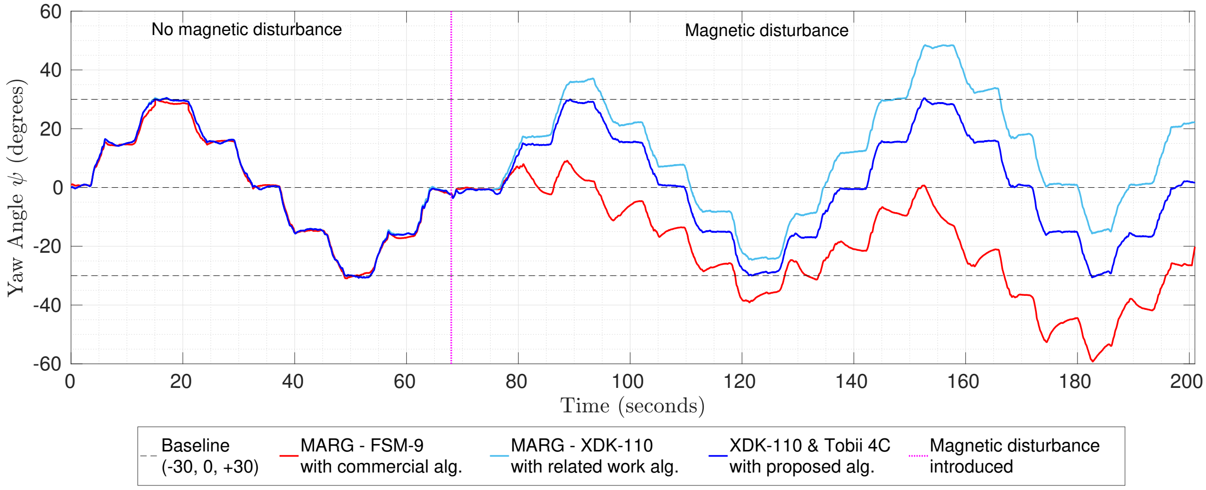

Fig. 5. Typical results for estimated yaw angle ψ from commercial sensor fusion from the FSM9 (red), the proposed visual and MARG fusion method consisting of the XDK-110 and Tobii eye tracker 4C (blue) and the proposed method without visual correction (light blue). The left hand side depicts data without magnetic disturbance. After 68 s magnetic disturbance is introduced by bringing an iron bar close to the MARG sensors (magenta vertical line).

method also eliminates the need for magnetometer calibration in environments that are subject to fast magnetic field changes. In such an environment, the fusion method will use visual heading (yaw) data and attitude (roll and pitch) data from the IMU equations for a complete orientation estimation. Furthermore, the proposed fusion method is able to overcome short time magnetic disturbance even when no visual information is valid by switching from MARG to IMU like data fusion inside the Kalman filter. This enables a robust and stable head motion estimation regardless of magnetic disturbances. The proposed system might furthermore be used to steer a wheelchair when mounted onto it or be used as a head-mouse to interact with a computer, e.g. writing a text in a zoom-in based text-editor.

VI. Future Work

Future research will include trajectory computation from the proposed MARG and visual sensor system to enable more control mechanisms in human-machine-interfaces, e.g. wider scope for gesture based control including position or trajectories. Furthermore, the integration of eye tracking or gaze data will be included to build a multimodal interface with more control outputs for a user to improve usability. Advanced specifications of precision of the proposed fusion method will be explored by comparing the proposed system with other absolute heading reference systems, e.g. infrared motion tracking.

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