

3D MOTION TRACKING OF THE PHILIPS HAIR STYLING APPLIANCES

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ABSTRACT

3D motion tracking of the Philips hair-styler

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The goal of the project was to study various three-dimensional motion tracking methods and to conclude on the system that can be implemented with Philips hair styling products. The assignment includes tracking such motion characteristics as: orientation, speed and position of the appliance. For the hair styling application the desired technical solution should also provide tracking motion of the appliance relative to the motion of the user's head.

The research and comparison of possible motion tracking techniques was performed and concluded that inertial – vision tracking is the most suitable solution for the given application.

Literature research, theoretical estimations and tests were performed in order to answer on to what extend inertial tracking can be used for motion tracking of the appliances. The main source of position and speed errors in inertial tracking is the inaccurate gravity compensation that is the result of orientation measurement error. Theoretical calculations were made that show possible accuracy of inertial speed and position tracking depending on the orientation errors. The tests for orientation, speed and position tracking were made with the chosen low-cost BNO055 inertial measurement unit that integrates sensor fusion algorithm and automatic sensor calibration. The tests showed that orientation tracking with the sensor is accurate with the error lower than 0.06 degrees. Based on both estimations and performed tests it is concluded that speed and position tracking with inertial sensors even with tracking time of under 10 s is not feasible for the application. The performed tests and research are important, because they allows to understand what accuracy of motion tracking can be expected from different sensors, especially taking into account the fact that inertial modules are currently being very rapidly developed.

Vision tracking with application of Microsoft Kinect depth camera is chosen to be the main solution for the application. Kinect skeleton tracking functionality is used to localize the hand of the user and therefore conclude on the position of the appliance. A set of tests were performed to check the accuracy of the Kinect position and speed tracking of hand and hand holding the appliance. The tests were made with a hand attached to the test equipment set to move with the speeds of 0.5 [m/s] and 0.05 [m/s]. The test results are presented in the chapter 5, tables 5.7 and 5.8.

As a result of the project of the formulated research question were successfully answered. It is currently not feasible to integrate the developed technical solution with products on the market. However, based on the project results it is possible to implement the motion quantification set up that would allow to analyze the user behavior at the product research center.

The main recommendations for the next steps of the project would be to implement an algorithm for separation of hand and appliance by color that would have minimum influence on the frame rate. Combining the separation algorithm with more advanced filtering that currently used will allow accurate speed tracking of the hand holding the device. Detailed recommendations are presented in chapter 6.

DECLARATION

I hereby certify that this report constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the report describes original work that has not previously been presented for the award of any other degree of any institution.

Signed,

Mykyta Pashkov

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CHAPTER 1 – RATIONALE

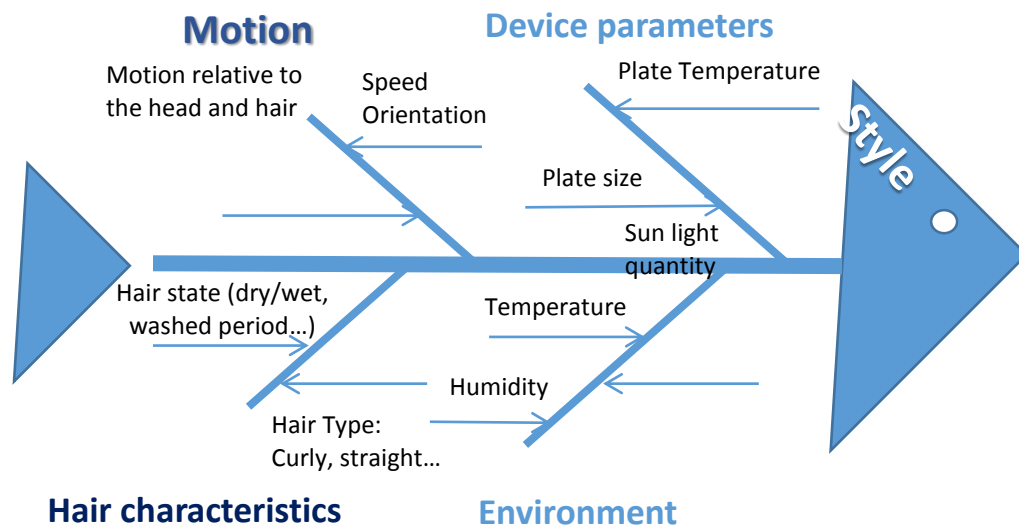
1.1 Reason for the research

Philips Haircare department is aiming for developing innovative and intelligent products with personalized user experience.

Within Philips Female Beauty department there was a hypothesis developed that motion tracking and the feedback can improve the hair-styling process. PRC (product research centre) performed a research focused on determining how hair-styling results are dependent on the motion characteristics. The tests and conclusions on the influence of motion characteristics of the appliance on the hair style are presented in the internal Philips technical report AST 235F-151116.

The simple fishbone diagram shows the influence of different factors on the resultant hair style.

Figure 1.1 Fishbone diagram, the influence of different factor on the hair-style



Hair style is dependent on such motion parameters as: rotation of the appliance, speed of the appliance. It is also important at what exact position relative to the head a rotation or other styling movement is made. Therefore it is desirable to have a system that will allow tracking 6 DOF (Degrees Of Freedom). There is also a hypothesis from PRC that speed of the appliance can influence the amount of hair damage due to temperature. The hypothesis is discussed in technical report AST 235F-151116. At very low speeds hair is heated up for a longer time that can increase the amount of damage.

There could be three main applications of the motion tracking for hair-styling:

1. Quantification of the motion. A system can be placed in the PRC testing room that would allow to quantify the motion of the appliance when it's used by the customer. The motion data for each user can be stored in the database that will allow to further draw statistical conclusion on the hair-styler use.
2. Guide the user during the styling process. Provide real time recommendation and feedback that will help achieve a desired styling result.

3. Position tracking of the device relative to the head can be useful when it is combined with a hair analytics products that are currently in the development. The combination could allow creation of the hair map showing certain parameters.

The goal of the project is to study various three-dimensional motion tracking methods and conclude on the system that can be implemented with Philips hair-stylers. It should be mentioned that that research can be applied to any Philips hair-straightener or styler. The assignment includes tracking such motion characteristics as: orientation of the device, velocity and position relative to the user's head.

At the current stage there is no motion tracking systems implemented in the haircare products, therefore the outcomes of the research can bring value to the future products.

1.2 Research questions

Main research questions:

Can the system be designed and developed that will allow tracking such motion characteristics of the Philips hair-styler as: orientation of the device, velocity, position of the device as well as the orientation and position of the device relative to the user's head?

Research sub questions:

What motion tracking techniques are the most suitable for tracking motion characteristics of Philips hair-styler?

To which extend the chosen motion tracking techniques can be applied for the motion tracking of the Philips hair-stylers?

What will be the performance of the developed system? If it is not possible to conclude on the accuracy of tracking certain motion parameters, the discussion and description of performance should be given?

CHAPTER 2 – SITUATIONAL & THEORETICAL ANALYSIS

Motion Tracking Techniques: Orientation, velocity and position tracking

2.0 Situational analysis introduction

The goal of the project is to find a solution to orientation, velocity and position tracking of the appliance. There are no detailed technical requirements for the given application, however the goal is to choose the system design that would provide most effective solution.

There are certain application specifics that should be taken into an account. The length of the hair styler movement is dependent on the hair length and can vary approximately from 5 to 60 cm. The hair-styling appliances can be moved and rotated in very different ways during the use, so there are no specific motion patterns that can be distinguished or classified. Simultaneous tracking of the appliance and the head of the user is preferred. This information is obtained from the discussion and consumer tests reports of product research centre.

There are no requirements set for orientation, speed and position tracking resolution and accuracy, the assignment is to find solution that would provide better results than alternatives and conclude on the possible technical characteristics.

There are no size requirements, the goal is however to find a portable solution. There are also no specific cost requirement, however less expensive solution that is feasible in implementation is preferred.

As well as that the system design that will provide a lower latency and higher sampling rate is preferred.

Different motion tracking techniques are researched and compared in order to develop a technical design that would provide an optimal solution. The results and conclusions of the research are presented in this and the following chapters.

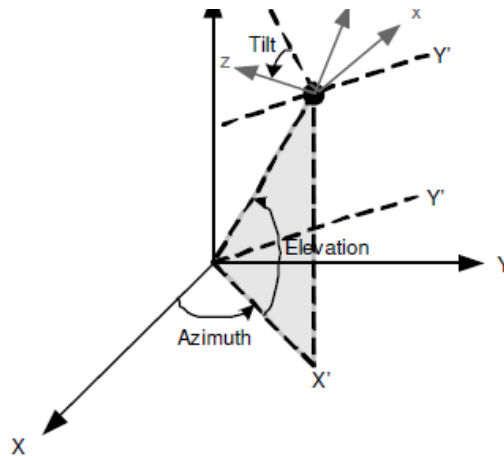
2.1 Tracking an object in space

The main idea of trackers is to provide the location and orientation information of an object relative to some coordinate system. To define the object in space, the tracker should give six pieces of information: three about the position, and three about the orientation. Such trackers present six degrees of freedom. The 3D position and 3D orientation of an object in space can be defined by the Cartesian coordinates X, Y, Z , and the Euler angles azimuth (θ), elevation (ϕ) and tilt (ψ). The angles are also called roll, pitch and yaw that is very popular in avionics and aeronautics. [4]

The azimuth angle θ is defined as a rotation of the X and Y reference axes about the Z reference axis. The transition axes labeled X' and Y' represent the orientation of the X and Y axes after the azimuth rotation. The elevation angle ϕ is defined as a rotation of the Z reference axis and the X' transition axis about the Y' axis. The transition axis Z' represents the orientation of the Z reference axis after the elevation rotation. Moreover the current x axis of the object represents the orientation of the X' transition axis after the elevation rotation.

The pitch angle ψ is defined as a rotation of Y' and Z' transition axes about the x axis of the object frame. The y and z axes of the object frame represent the orientation of the Y' and Z' transition axes after the tilt rotation.[1]

Figure 2.1 X, Y, Z = Reference frame, x, y, z = Object coordinate frame, Azimuth, Elevation, Tilt = Euler angles. [1]



When tracking orientation of the appliance it is assumed that there are three frames of reference. World frame (Gravity, North reference), one body frame of the device and one body frame of the user head. The goal is to track the rotation of the device's body frame relative to the earth frame. Additional goal is to track the rotation and position of the device's frame relative to the human head frame.

2.2 Motion tracking techniques

There is a great variety of motion tracking techniques, each one has unique strengths and limitations. Tracking technologies can be separated into three categories: active-target, passive target and inertial.

- **Active target systems** are based on powered signal emitters and sensors as receivers. Such systems use magnetic, optical, radio and acoustic signals.
- **Passive-target systems** use ambient or naturally occurring signals. Such systems include Vision tracking, Earth's field sensing with magnetometers.
- **Inertial systems** are self-contained and operate by sensing linear acceleration and angular motion.[2]

Hybrid systems are designed in order to compensate for the weaknesses of each technique.

Table 2.1 Hybrid motion tracking systems

Hybrid Systems	Examples
Active-Active	optical-electromagnetic
Active-Passive	magnetic-vision
Active-Inertial	optical-inertial
Passive-Inertial	compass-inertial

In the following chapter main motion tracking techniques will be discussed in more details.

2.2.1 Radio and microwave sensing

Radio wave sensing techniques are widely used in navigation systems and also can be used in local positioning systems. [4]

The main advantage of the electromagnetic wave-based tracking techniques over magnetic sensing is that it can provide vastly greater range than quasi-static magnetic fields because radiated energy in a field of radius r dissipates as $1/r^2$, whereas the dipole field strength gradient drops off as $1/r^4$. [2]

Location tracking approaches

Location tracking and positioning systems can be classified by the method the mobile device location is determined. There are three basic categories of systems that determine position that are based on measuring the following:

- Distance (lateration)
- Angle (angulation)
- Location patterning(pattern recognition)[3]

Distance measuring techniques

Time of Arrival

Time of Arrival (ToA) systems are based on the precise measurement of the arrival time of a signal transmitted from a mobile device to a number of receiving nodes. The distance between the mobile device and each receiver can be determined from the elapsed propagation time of the signal traveling between them, because signals travel with a known velocity. With distance used as a radius, a circular representation of the area around the receiving sensor can be constructed for which the location of the mobile device is highly probable. *Trilateration* is used to determine the mobile device position from the ToA measurement.[4]

Trilateration is a positioning technique, which estimates the mobile node's location by intersection of the circles, each centered on the anchor node position, with a radius that equals to the estimated distance between the mobile node and the anchor node. The required number of anchor node for localization in p dimensional space is $N = p + 1$. The estimated location is defined by the center of the region formed by the intersection of the circles. There is a different approach where the number of required anchor nodes is $N = p$. The method records intersection points in consecutive time frames and estimates the intersection location by the closest distance.[5]

Figure 2.1 The principle of tri-lateration. [4]

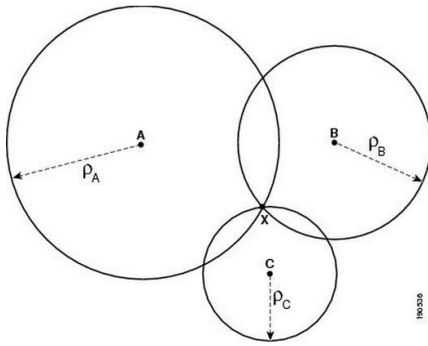
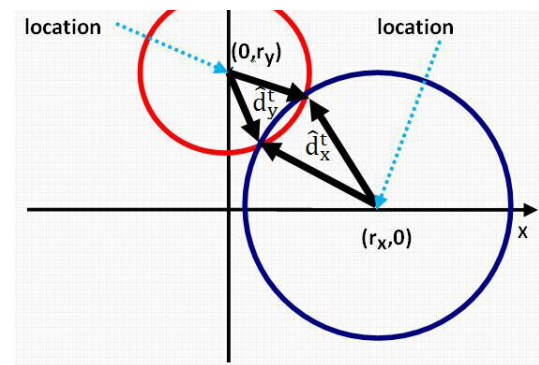


Figure 2.2 Intersection of 2 anchor node's circles. [4]



3D positioning can be performed by constructing spherical instead of circular models.

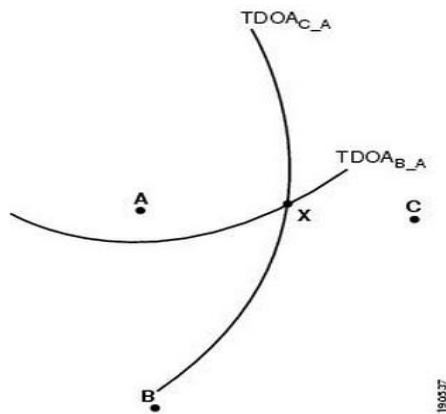
The main disadvantage of the ToA method is that precise time synchronization between all nodes is required. With a high propagation speeds of a signal, small time synchronization errors can result in a very large errors in location estimation. As well as that ToA system accuracy is influenced by signal multipath, interference and other noise within environment [4].

One of the most accurate localization techniques that are based on ToA estimation is **Ultrawideband (UWB) ranging**. UWB ranging makes use of non-sinusoidal electromagnetic signals such as impulses. The outstanding advantage of the UWB paradigm is the improved ability to reject multipath signals. With pulses as short as 200 ps, all reflection paths delayed by 6 cm or more can be easily disregarded.[6]

Time Difference of Arrival (TDoA)

Time Difference of Arrival (TDoA) techniques are based on relative time measurements at each receivers. With TDoA, a transmission with an unknown starting time is received at various receiving sensors, where only receivers require synchronization. TDoA needs at least three time-synchronized receivers. The position of the moving node is estimated with *hyperbolic lateration*, where using recorded time difference of arrival between nodes, hyperbolas that show all possible locations of the mobile device are constructed and the probable location is estimated at the intersection of the resulting hyperbolas.[5]

Figure 2.3 Tdoa hyperbolic iteration



Location tracking with RSSI

RSSI (Received Signal Strength Indicator) is a signal power on a radio communication link that is used as a ranging technique in Wireless Sensor Networks (WSN).

The advantages of the conventional RSSI localization system is simplicity, low power consumption and low cost of implementation. The main disadvantages of the method of the system are:

- requirement of minimum 3 receivers for three-dimensional positioning;
- resolution in order of meters;
- communication channel distortion

A number of researchers presented their works where the conventional algorithms were improved that resulted in the higher tracking resolution.

Alternative RSSI based localization method was developed at the University of California at Berkeley that included advanced processing techniques to mitigate over channel distortion and packet loss, used fewer sensor nodes and reached the accuracy of distance estimation to scale of few centimeters, in the conditions of close proximity between nodes and a clear Line Of Sight (LOS). [7]

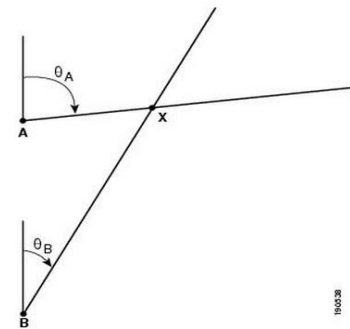
Another work presented [8] showed obtained approximation error of up to 10 cm using raw RSSI measurements, in proximate environment, with accurate calibration and LOS conditions. The work described in [5] implement histogramic analysis and statistical filters for RSSI processing that improve the accuracy range.

Angle of Arrival (AoA)

The *Angle of Arrival (AoA)* technique estimates the position of the moving node by determining the *angle of incidence* at which signals arrive at the receiving sensor. The location of the node can be found with geometric relationships the intersection of the lines of bearing formed when angle of arrival is known, shown in the following figure. Minimum 2 receivers are required to determine the 2d location. [5]

A common drawback that AoA shares with other positioning techniques described is influence by multipath interference. AoA works well with direct line of sight, however suffers from decreased accuracy and precision when confronted with signal reflections from surrounding objects. AoA is more effective with signals that has a lower propagation speed, such as acoustic signals [6].

Figure 2.4 Angle of Arrival



Location Patterning Techniques

Location patterning is based on recording radio signal behavior patterns in a given environment. Location patterning technique is operating by measuring RSSI at the mobile device from an array of RFID tags. The main assumption of the method is that each device location results in a distinctly unique RF "signature". The first step of patterning-based localization systems is calibration phase during which the RSSI data is accumulated by moving the device in the given environment and a *radio map* or *training set* is developed. During the next operation step of the system the RSSI detected and position is determined with by comparison of received data with calibration sample set using different deterministic, probabilistic or machine learning algorithms. The RFID based localization systems are presented in a number of selected papers and patents [4]

Patents/Research Papers/Commercial products

Patent for Motion Tracking with RFID[9]
Indoor position estimation system with passive RFID system [10]
Open source UWB based tracking platform [Pozyx](#)

Advantages:

- Radio waves do not suffer from absorption losses in air.
- No clear line of sight required
- The location tracking with RSSI can be quite low cost.

Limitations:

- RF positioning systems require minimum 3-4 references for 3d positioning.
- Resolution of RF tracking systems are normally within meters, only with a very controlled environment and complex algorithms can be as accurate as few cm.
- RF tracking systems based on ToA and TDoA require time synchronization between nodes.
- Implementation of the most accurate systems like UWB ranging systems can be relatively expensive.

Discussion

RF tracking systems are used for position tracking and wouldn't be suitable for orientation tracking. The RF systems based on the ToA and TDoA are not very suitable for the hair-styler mainly due to the requirement of node synchronization. RFID tracking is not very suitable due to required large number of RFID tags. A number of papers present an application of new algorithms based on RSSI measurement that result in location resolution accuracy of 4-10 cm with clear Line of Sight. Taking into account a relative low-cost of the RSSI measurement, such method could be considered for localization of hair-styler. The drawback of all RF tracking systems is the fact that minimum 3 receiving nodes would need to be placed on the head of the user that makes all of the RF tracking systems no very suitable for Philips hair-styler. However if hybrid system is developed, RF positioning still can be considered as an option.

2.2.2 Optical Sensing

Optical systems rely on measurements of reflected or emitted light. These systems consist of two components: light source/emitter and optical sensor/receiver.

The light sources might be passive objects that reflect ambient light or active devices that emit light. Optical sensors can be either analog or digital devices. Analog sensors output voltages that are proportional to the intensity or centroid position of the light reaching the sensor. Digital sensors output a discrete image of the scene projected on the sensor. Optical sensors can be 1D or 2D. [11]

Types of optical sensors:

- *Photo-sensor* - a device that simply changes resistance as a function of the quantity of light reaching it.
- *An analog position sensing detector (PSD)* - is a 1D or 2D semiconductor device that produces a set of currents that indicate the position of the centroid of the light reaching the sensor. Such sensors combined with active light sources offer the combination of relatively high spatial precision and update rates
- *Digital image-forming devices*, charge-coupled devices (CCDs)

Imaging sensors can be used with active, retro-reflective, or passive targets.[12]

Outside-In or Inside-Out

When designing an optical tracking system the choice must be made whether to put the light emitter on the target and the sensor/receiver in the environment or vice versa. Therefore optical trackers can be classified into “outside-in” and “inside-out” systems where in outside-in the emitter is placed on the target and in inside-out the light source is in the environment. [3]

The main application of the optical tracking systems is the use of multiple optical sensors/receivers in known locations to estimate the position of a light source relative to the sensor with triangulation or multibaseline correlation estimations.

Advantages:

- Optical systems with active light emitter offer a high spatial precision and update rates.
- Passive optical systems with cameras/image output devices allow motion tracking without active emitter placed.[2]

Limitations:

- The main disadvantage of all optical systems is that there must be a clear line of sight between the source and the sensor.
- Active optical systems can require a multiples of light emitter and receivers.
- Image-forming passive systems do not require active light sources, however are typically limited to relatively few measurements per unit of time.
- Algorithm for motion detection from image-forming systems is computationally intensive.[3][4]

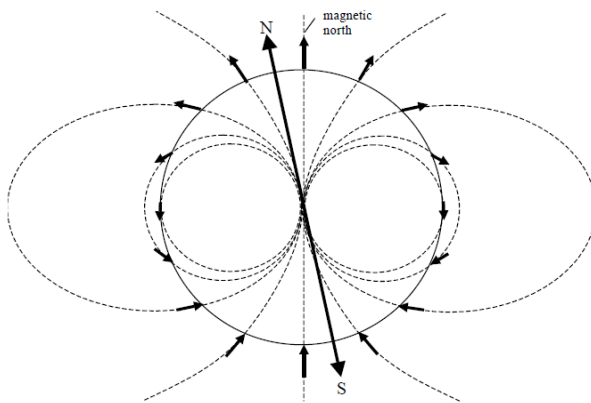
Discussion:

Digital image-forming systems can be very suitable for the motion tracking of Philips hair-styler. Web camera build in smartphone, tablet or other device could be potentially used for the tracking of both object and head of the user. The limitations of the system are: the line of sight that requires the person to be in front of the camera as well the fact that some of the computer vision algorithms could be to computationally intensive to run on the smartphone, however it is very dependent on the chosen computer vision technique.

2.2.2 Magnetic Sensing

Magnetic systems rely on measurements of the local magnetic field vector at the sensor, using magnetometers (for quasi-static direct current fields) or current induced in an electromagnetic coil when a changing magnetic field passes through the coil (for active-source alternating current systems). Three orthogonally oriented magnetic sensors in a single sensor unit can provide a 3D vector indicating the unit's orientation with respect to the excitation. A current applied to the source coils will generate a magnetic dipole field (Figure 2.2). At the receiver, this will induce a maximum voltage proportional to the magnetic field strength if the receiving coil is oriented in the same direction as the magnetic field. Therefore the induced voltage measured at the receiver gives information both about the distance from the transmitter to the receiver and the axis alignment between them. [1]

Figure 2.5 Magnetic dipole [2].



Magnetic sensing can also be classified into an active and passive systems.[3]

Active systems include multi-coil source unit as a magnetic field generator and field sensing coils as a sensor unit. Where each of the coil at the source unit is energized in sequence and the change of the magnetic field vector is measured at the sensor unit coils. With three such excitations, it is possible to estimate the position and orientation of the sensor unit relatively to the source unit.[13]

Passive system are based on the geomagnetic Sensing (earth's magnetic field sensing), where heading (yaw) of an object can be determined with application of a magnetometer. In the following researches, magnetic field generated by permanent magnet was sensed by a number of magnetometers.[14]

Advantages

- Magnetic sensing doesn't require line-of-sight, magnetic-fields passes through the human body.
- A single source unit can be used to simultaneously excite and track multiple sensor units.
- Size of the components can be compact.

Limitations

- The interferences with ferromagnetic objects, mainly in steel or iron.
- The range of operation is very limited. With both AC and DC active source systems, the useful range of operation limited by the inverse cubic falloff of the magnetic fields as a function of distance from the source.
- Position resolution in the radial direction from source to sensor depends on the gradient of the magnetic field strength, and thus the positional jitter grows as the fourth power of the separation distance.[4]

Commercial products

Northern Digital Inc. – Electromagnetic systems supplier for Philips

Sixsense STEM gaming system

Tracking system to monitor the position and orientation of a device using multiplexed magnetic resonance detection.

Discussion

Electromagnetic system with active AC or DC source can be a very effective solution for the Philips hair-styler. The main limitation of the system is disturbance of the system due to ferromagnetic objects or other electronic devices that are close to the system. As well as that the cost of the electromagnetic system can be relatively high. Due to the fact that there is research going on the electromagnetic device tracking in the Philips shaving department, electromagnetic systems will not be studied within this thesis in very details, however development of hybrid system that will improve the performance of the electromagnetic system will be taken into an account.

2.2.3 Acoustic sensing

Acoustic systems use the transmission and sensing of sound waves. Most commercial acoustic ranging systems operate by timing the flight duration of a brief ultrasonic pulse. The time-of-flight (TOF) ranging technique is the most successful in solving the problem of multipath reflections. [12]

Multipath, refers to the fact that the signal received is often the sum of the direct path signal and one or more reflected signals of longer path lengths. Since walls and objects in a room are extremely reflective of acoustic signals, the amplitude and phase of the signal received from a continuous wave acoustic emitter in a room will vary drastically and unpredictably with changes in position of the receiver. An outstanding feature of pulsed TOF acoustic systems is that it is possible to overcome most of the multipath reflection problems by simply timing until detecting the first pulse that arrives, which is guaranteed to have arrived via the direct path unless it is blocked. The reason this simple method works for acoustic systems but not for RF and optical systems is the relatively slow speed of sound, allowing a significant time difference between the arrival of the direct path pulse and the first reflection.[2]

Advantages:

- Acoustic sensing can be implemented low-cost.
- Depending on the active surface area of the sound sources and microphones the ultrasonic trackers can offer a large tracking range.

Limitations:

- Acoustic systems require a line of sight between the emitters and the receivers, but they're more tolerant of occlusions than optical trackers.
- Acoustic systems' update rate is limited by reverberation. Depending on room acoustics and tracking volume, it may be necessary for the system to wait anywhere from 5 to 100 ms to allow echoes from the previous measurement to die out before initiating a new one, resulting in update rates as slow as 10 Hz.
- Accuracy can be affected by wind (in outdoor environments) and uncertainty in the speed of sound, which depends significantly on temperature, humidity, and air currents[15]

Discussion:

Line of sight is the main limitation that makes ultrasonic or acoustic waves not suitable for position tracking of the Philips hair-styler. As well as that minimum 3 receivers should be placed on the head of the user in order to determine relative position of the device. Some of the hair treatment devices can in future include ultrasonic emitters that would interfere with the system.

2.2.4 Inertial sensing

Inertial motion capture relies on acceleration and rotational velocity measurements from tri-axial accelerometers and gyroscopes. The technology is based on Newton's second law of motion, $F = ma$, and its rotational equivalent, $M = I\alpha$. [2]

Accelerometers are used to measure the acceleration of an object's position along one axis and gyroscope is used for measuring object's orientation around one axis. When three axis accelerometers and three axis gyroscopes are used it is possible to get a 3D position and 3D orientation measurement. [3]

The principle of accelerometers is to measure the force exerted on a known mass, and then derive the acceleration from the formula $F = ma$. An accelerometer is simply a mass attached to a spring with the spring constant k . The displacement x of the mass m from its center position is then measured. The acceleration is: $a = kx/m$. From the formula it can be observed that a spring will have a linear behavior only close to the null position. Therefore a closed-loop system with a forcer and an electromagnetic displacement pickoff is implemented in order to keep the mass close to the null position. The acceleration can then be determined by the amount of power the forcer needs to hold the mass in place. This kind of approaches are implemented using Micro-Electro-Mechanical-System (MEMS). [16]

Gyroscopes sense and measure the angular rate of an object. The first gyroscopes used spinning wheels mounted on gimballed platforms to determine roll, pitch and yaw from the angles of the gimbal's axle. MEMS development allowed creation of new small, light and low-cost gyroscopes Coriolis Vibratory Gyroscopes (CVG) that replaced spinning wheels with a mass that oscillates at a very high frequency. A pickoff measures the secondary vibration mode caused by a Coriolis force.

The problem with tracking orientation using only gyros is drift. There are several causes of drift in a system that obtains orientation by integrating the outputs of angular rate gyros:

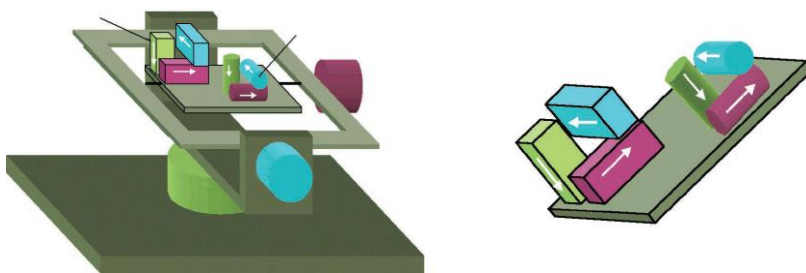
- **gyro bias**, $\delta\omega$, when integrated causes a steadily growing angular error $\phi(t) = \delta\omega \cdot t$
- **gyro white noise**, when white noise is integrated, the result should be 0 (when integrated over a long enough time), but the mean squared error will grow linearly in time.
- **calibration errors** in the scale factors, alignments, and linearities of the gyros, produce measurement errors which look like temporary bias errors while turning, leading to the accumulation of additional drift proportional to the rate and duration of the motions.
- **gyro bias instability** means that even if the initial gyro bias is known or can be measured and removed, the bias will subsequently wander away, producing a residual bias that gets integrated to create a second-order random walk in angle. Bias stability is usually modeled as a random walk or Gauss-Markov process, and is often the critical parameter for orientation drift performance, since constant gyro bias and deterministic scale factor errors can usually be calibrated and compensated effectively.

Inertial Measurement Unit

A sensor, consisting of a three axial accelerometer and a three axial gyroscope, approximately mounted in one point is called an Inertial Measurement Unit (IMU). In theory, a calibrated IMU measures 3D angular velocity and 3D acceleration and gravity with respect to the sensor housing. Given an initial position and orientation, ideally these signals would contain sufficient information to derive the IMU kinematics completely. The orientation can be obtained using a known initial orientation and the change in orientation that can be obtained using gyroscopes [4].

The resulting orientation can be used to subtract the gravity from the 3D accelerometer vector to yield an acceleration. Expressed in a nonrotating reference frame, double integration of the acceleration yields the position change.

Figure 2.6 Accelerometer and Gyroscope model [12]



Advantages:

- No line-of-sight requirements
- Angular rate measurement with very low noise due to gyroscope application
- No emitters/receivers system
- Very low latency, very high sampling rates
- No sensitivity to interfere with ambient noise or electromagnetic fields

Limitations: Bias drift that doesn't allow accurate position tracking

Discussion

Inertial tracking can be successfully applied to tracking orientation of the device and such advantages as no line-of-sight requirements and low latency make inertial tracking a good potential technique that could be combined with another position tracking technique.

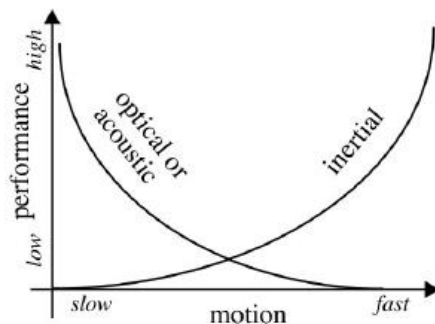
The Summary of all the tracking techniques is presented in the Table 2.2.5 found in the appendix part A.

2.2.6 Hybrid Systems

Every tracking system has its limitations and weaknesses. By combining two or more tracking devices to a hybrid system, the weakness of one single system can then be compensated by the other one. Producing a tracking system that has a performance over a wide spectrum of applications. Most hybrid systems are based on inertial tracking and extended by low frequency tracking system that provides absolute position data.[17]

Inertial tracking provides the best solution for the orientation tracking at high frequencies and during fast motion, however gives less accurate data at low frequencies. Accurate positioning data can be obtained only on the time scale of [ms]. Therefore combination of the inertial tracking with another system such as optical or electromagnetic that can track position and orientation without drift, is an effective solution.

Figure 2.7 Comparison of the performance of inertial vs optical and acoustic systems at different motion speed levels [16].



The hybrid system could be developed based on combination of different orientation and position tracking techniques discussed above in the chapter.

2.2.7 Discussion/Conclusion

In the Chapter 2, various motion tracking techniques were analyzed. All advantages and limitation of each method were described. From the description it can be concluded that the inertial tracking is a great solution for the orientation tracking. Optical tracking is another very solution that can potentially be used for both position and orientation sensing. Orientation sensing with a camera can be difficult in the given application, because the appliance is quite often not visible for the camera and object tracking algorithms can't not be effective. One camera can provide only two dimensional position data. In order to get three axis data, depth cameras could be used. Depth cameras could also allow more accurate orientation tracking (more information on the Depth sensor will be presented in the next chapter).

Other motion tracking techniques are less feasible to be implemented separately.

The main conclusion of the chapter is that hybrid system is the solution that can provide the most optimal results. Therefore hybrid systems will be studied and compared in more details.

PART 3 – CONCEPTUAL MODEL

3.0 Hybrid Systems Comparison

The conceptual model of the technical solution can be divided into following parts:

1. Orientation tracking of the appliance with IMU. Short-term, not accurate, speed and position tracking with IMU.
2. Position tracking
3. Orientation and position tracking based on the hybrid system

There are no detailed technical requirements for the given application, however the goal is to choose the system design that would provide most effective solution.

From the research on various orientation, speed and position tracking techniques it was concluded that hybrid systems is potentially the most suitable solution.

The comparison of different possible motion tracking systems are described in the following table 3.1.

Discussion/Conclusion

From the comparison of possible hybrid systems it can be concluded that inertial-vision systems and inertial-electromagnetics system are the most suitable for the orientation and position tracking of the hair-styler. Inertial tracking with magnetometers and passive magnets could be effective low-cost solution, however the accuracy of the system on the ranges of hair-styler motion are expected not to be accurate, as well as that magnetic distortion can have a very strong influence on the accuracy of the system. From the literature research only a number of papers presented a system for RSS position tracking with 4-10 cm resolution where the tests were performed in a very constraint environment. [7] The RSSI tracking with conventional algorithms and less constraint environment normally shows significantly lower resolution that makes the inertial-RSSI tracking not very suitable for the application. The Inertial-UWB tracking can show a higher resolution and accuracy, however due to relatively high cost and a requirement of a big number of receivers placed at different height levels it is not the most suitable solution.

Inertial –electromagnetic system is not feasible in implementation due to relatively high price, low portability and high complexity.

Inertial-vision tracking is concluded to be the technique of choice for the given application. Inertial-vision tracking has another benefit, potentially it can be used with an external camera that is built in users devices could be used and therefore such system will not influence the price of the product.

In the next part of the chapter more detailed research and discussion on possible implementations of inertial – vision tracking systems will be presented.

Based on the conclusion the second and third research sub-questions can be defined to be more specific:

To which extend inertial sensing method with application of accelerometers, gyroscopes and IMU sensors and chosen vision tracking method can be applied for motion tracking of the Philips hair-styler?

What is the accuracy of the orientation, position and speed tracking of the developed inertial - vision system?

Table 3.1 Hybrid Systems Comparison					
Hybrid system	Description	Advantages	Limitations	Conclusions	Examples
Inertial-vision	The combination of the IMU and a camera in front of the user. IMU can provide a low-latency orientation data and a very short term velocity, position data. With camera it is possible to obtain accurate position and orientation data with lower latency. Fusion of inertial and vision system can result in a very accurate and robust system.	• Fast response, low latency due to IMU • Accurate position and orientation • Relatively low-cost of implementation, camera from the user's device (smartphone, tablet) can potentially be used. • Can track both object and a head orientation/position at the same time • portable	• Line of sight requirement for position detection, user need to be in front of the camera. • Indoor lighting can have an influence on the accuracy of the system • When camera is not operating position data will be not accurate • Might require a lot of processing power on the external camera device.	Inertial-vision system can be a very effective solution for Philips hair-styler. The only point of consideration is that user will need to use additional device with build in camera or depth-camera while using the product.	Oculus RIFT , VR gaming head mounted display
Inertial – visual with camera on the device(optical flow algorithm)	The combination of the IMU and a camera on the device. Optical flow algorithm can be applied in order to determine position and orientation of the appliance from the camera integrated into the appliance itself.	• Fast response, low latency due to IMU • Position tracking with high resolution • portable	• Separate IMU need to be placed for tracking head of the user • Can be quite expensive • Optical flow requires a lot of processing power	The solution should be taken into an account because it can provide required results, however due to relatively high price and required processing power on the appliance this solution might be not the most effective.	Optical flow open source camera with built in IMU Papers:[18],[19],[20]
Inertial-electromagnetic	Combination of IMU and an active electromagnetic system with an AC/DC generator and receiver coils for position and orientation sensing	• No line of sight requirements • Accurate orientation and position tracking • Can track both absolute and relative to the user's head orientation and position. • Portable	• Position tracking accuracy can be influenced by the environmental magnetic interference • Receiver sensors need to be placed on the head of the user. • Price of the system can be relatively high	Inertial-electromagnetic system can be an effective solution for Philips hair-styler. Adaptive calibration algorithms could be investigate to improve the problem of magnetic interference.	Sixsense STEM gaming sytem The main example is the new tracking system developed within Philips.

Inertial-passive magnetic	Combination of accelerometer, gyroscope, number of magnetometers and a permanent magnet.	• No line of sight requirements • Accurate orientation and position tracking within short distance ranges • Can track both absolute and relative to the user's head orientation and position. • Portable • Relatively low-cost	• Can be accurate only within very short ranges • Position tracking accuracy can be influenced by device's and the environmental magnetic interference • Magnet or magnetometer need be placed on the	The main challenges of the system are the low-accuracy at longer distances. At the example applications, system was accurate only within range of around 15 cm and this accuracy was reached in conditions that excluded any magnetic interference. The range would be much lower in the environment with the interference.	uTrack: 3D finger tracking[21] Google project Tango Paper on hand pose estimation with IMU and a permanent magnet [14]
Inertial – UWB	Combination of inertial tracking for orientation and ultra-wideband ranging based on Time of Arrival measurement (ToA) for position tracking.	• No clear line of sight requirements • Accuracy close to acceptable, the average error in advanced systems is about 10 cm	• Require min 4 receivers placed at different height levels • The price can be too expensive	The system is not very suitable for the application mainly due to high price and a big number of receivers that must be placed on the head of the person. However is worth mentioning, because it is the most precise tracking option from existing RF positioning systems.	Pozyx - the first open source inertial-UWB positioning system that is in the development. Research paper on UWB/IMU pose estimation[20]
Inertial - RSSI	Combination of inertial tracking with measuring RSSI of the RF signal for position tracking	• No clear line of sight requirement • Relative low cost	• Require minimum 4 or 3 receivers places • Low accuracy in the range of meter. Only a number of research papers showed accuracy of 4-10 cm	The system is not very suitable due to low accuracy and a high number of receivers. Low cost and possibility of accuracy improvement are good points	Research papers showing results with acceptable accuracy [7]
Inertial-ultrasonic	Combination of inertial tracking for orientation tracking with combination of ultrasonic ranging for position tracking	• Low-cost, relative simplicity of implementation • Possible high accuracy of tracking	• Line of sight requirement. • Due to device rotation the signal transmission or receiving would need to be omnidirectional • For the given application there will be very high interference that would not allow accurate tracking. • Requirement of minimum 3 receivers for position tracking	The system is not suitable for accurate hair-styler localization around the users head.	Paper of hand tracking relative to head with ultrasonic system[22]

3.1 Vision Tracking. Microsoft Kinect.

In order to answer the formulated research question the designed technical solution needs to be able to track position and orientation of the hair-styler, position and orientation of the head of the user as well as speed of the appliance.

It must be noticed that tracking of the hair-styler as an object is not suitable because the appliance is usually rotated and moved in such a way that makes it not visible for the camera. Therefore computer vision algorithms for object tracking [31] can't not be used as the main solution. Hair-styler is handheld and as a result body joints together with hand tracking algorithms [32] can be used to determine the position, orientation of the appliance. Some of the object tracking methods can still be considered to be used in combination. Face tracking algorithms[23] can be used to obtain position and orientation of the head of the user.

The speed tracking of the hair-styler is one of the most important parts of the assignment. Accurate speed of the appliance can be determined only if position is tracked in three dimensions. The most effective way for obtaining a 3d position vector is an application of depth cameras that provide distance information.

Next, depth cameras and possible solutions for hand, object and face tracking with computer vision will be introduced and discussed.

3d cameras. Microsoft Kinect

3D cameras provide a 2d image and also output distance information to obtained pixels. The distance information can be estimated as the result of combination of a number of lenses with separate image sensors or by application of time-of-flight camera. ToF camera resolves distance by measuring time-of-flight of a light signal between the camera and the object for each pixel of the generated image [12]

There are a number of different depth cameras available on the market. For the given assignment 3d hand position tracking as well as face tracking is important. Microsoft Kinect is a depth camera that provides distance information based on the time of flight measuring principle. Kinect gives a number of data sources as an output, such as: Colour, Infrared, Depth, Body, Body Index, audio [33].

The following figures show different data sources available from Microsoft Kinect sensor.

Figure 3.1 Color source: resolution 1920 x 1080, frame rate 30fps [30]



Figure 3.4 Body index source [30]



Figure 3.2 Infrared source: 512X 424, 30 fps [30]



Figure 3.5 Body frame source

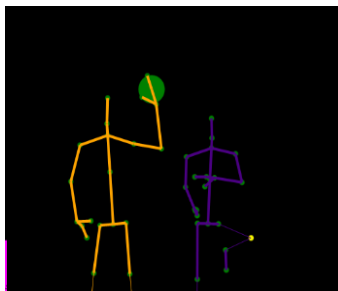


Figure 3.3 Depth frame , Tracking Range 0.5- 8m [30]



The main data sources of interest is Body Frame, skeleton tracking data source that gives 3d position and 3d orientation vectors for each of the 25 body joints as an output. It is possible to obtain Body Frame data for 6 people simultaneously for the range of 0.5 – 4.5 meters tracking with 30 fps. As well as that a separate face tracking algorithms are implanted within the Kinect API that can allow accurate human head position and orientation tracking [33].

The reason for choosing Kinect is availability of the skeleton tracking algorithms implemented within the Kinect development environment. All the other depth cameras currently available on the market do not provide integrated joint tracking algorithms, as well as that there are no solutions found that could provide better hand tracking results with an open-source available algorithms. From the literature research it is difficult to state on the accuracy of the hand speed and position tracking with Microsoft Kinect or different computer vision techniques. In one of the literature sources the accuracy of hand position tracking with Kinect sensor was estimated to be around 1- 5 cm. [36]. The latency of the system is expected to be around 60 – 80 ms. [33] that is sufficient for the real time feedback and the application.

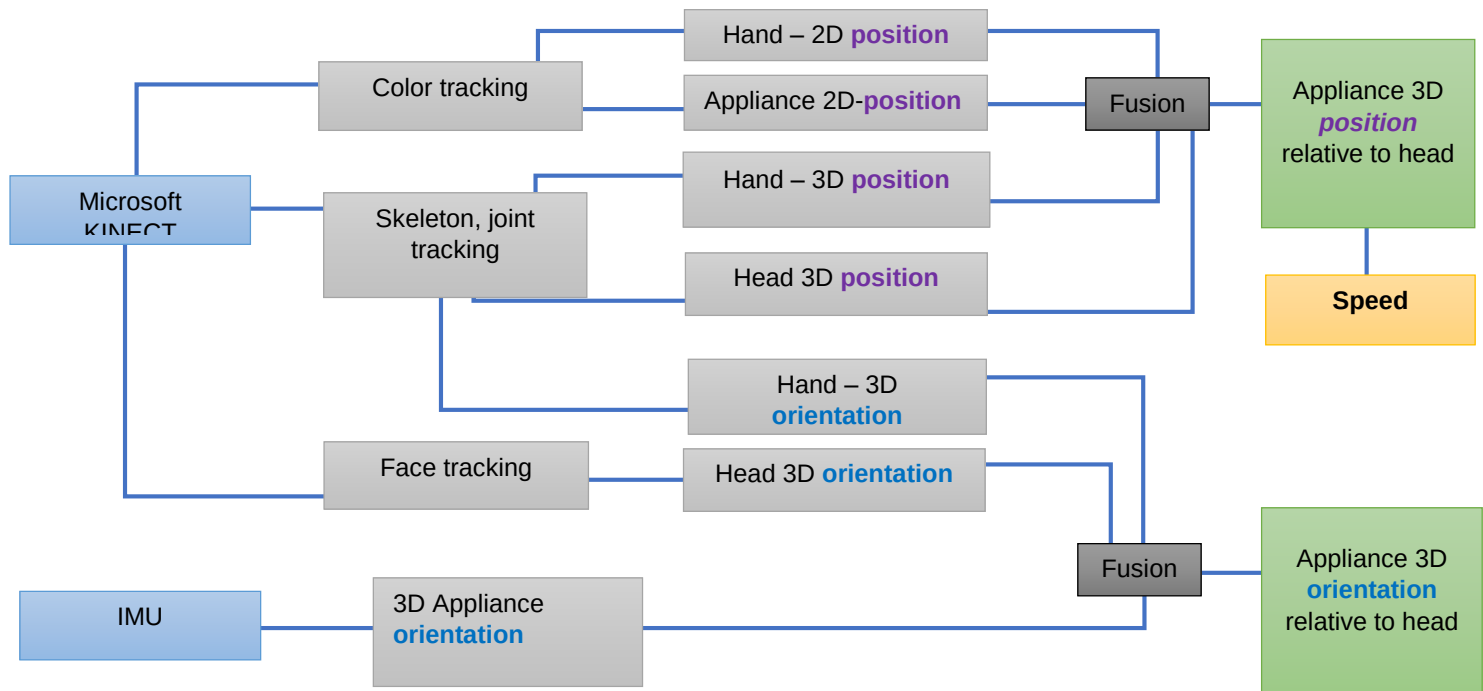
Development of custom hand tracking algorithm is not relevant at this stage of the project and is not expected to provide better results.

As a result Microsoft Kinect is chosen as the current solution and accuracy of the hand position and speed tracking will be tested within the project.

3.2 System Model overview

The following diagram summarises the implemented vision-inertial tracking system.

Figure 3.6 Diagram of the designed and implemented motion tracking application



3.3 Conclusions

As a result of the research on motion tracking techniques and comparison of possible hybrid systems, inertial-vision tracking system was concluded to be the most suitable and realistic solution. Research on possible vision tracking techniques that will allow tracking a hair-styler position and orientation relative to the head was performed. Hair styler users hold and move the device in very different ways and therefore object tracking by placing light emitters or reflective markers is not suitable. Object tracking with computer vision algorithms is challenging for the same reason. Therefore hand tracking is chosen to be a better solution. 3d position tracking of hands from web-camera is a challenging assignment. Application of a depth camera is significantly more feasible solution for the given project. Microsoft Kinect depth camera that allows 3d joint tracking is chosen as the main solution. The object colour tracking techniques could be together with Kinect skeleton tracking in order to separate hand-held device and improve hand tracking accuracy. IMU orientation tracking is more accurate than Kinect joint tracking and is not sensitive to occlusions. As well as that orientation of the hand is not exactly equal to the orientation of the appliance, therefore orientation data is also obtained from the IMU placed on the hair-styler.

CHAPTER 4 – RESEARCH DESIGN

4.0 Research design outline

The research questions were stated at the beginning of the project and defined to be more specific after choosing the motion tracking techniques for the technical solution.

In order to answer the research sub-questions, the developed system was tested in the following 2 steps:

1. Theoretical estimations on possible accuracy with inertial tracking were presented. IMU sensor was chosen. Orientation with the chosen IMU was tested. Short-term, speed and position tracking accuracy with the IMU sensor was tested.
2. Position and speed tracking accuracy of the hand and hand holding the appliance with Microsoft Kinect was tested.

The main research question consist of three sub-questions. In the research design chapter the details are given on how each research sub-question are answered.

4.1 Research sub-question 1

Sub-question 1:

What motion tracking techniques are the most suitable for tracking motion characteristics of Philips hair-styler?

The answer on the first sub-question was given in the chapter 2 and 3 and as a result the inertial-vision tracking systems was chosen as a final solution.

4.2 Research sub-question 2 and 3

Sub-question 2:

To which extend inertial sensing method with application of accelerometers, gyroscopes and IMU sensors and chosen vision tracking method can be applied for motion tracking of the Philips hair-styler?

Sub-question 3:

What is the accuracy of the orientation, position and speed tracking of the system developed based on IMU and Microsoft Kinect ?

In order to answer the stated sub-questions a prototype application with IMU orientation, and speed position need to be tested. As well as Kinect hand speed and position tracking

All the details on the research design and performed tests can be found in the flow diagrams 4.1 and 4.1 in the appendix part a.

The following parts of the chapter give an overview and a general background information on the orientation tracking with IMU. The part 4.2.2 gives general background information on calibration and calculation of gravity compensated linear acceleration.

However for the tests the BNO055 sensor was chosen that integrates both automatic calibration and integrated sensor fusion. The orientation is obtained directly from the BNO055 expressed as Euler angles for X, Y and Z axis. The gravity compensated linear acceleration is also obtained directly from the sensor and doesn't need to be estimated separately. The details on obtaining orientation and linear acceleration with BNO055 can be found in the datasheet [29]

4.2.1 IMU orientation tracking. Background information

The orientation tracking with Inertial Measurement Unit can be done by fusing raw data obtained from accelerometer, gyroscope and magnetometer.

IMU sensors scaling and conversion

The gyroscope outputs the ADC value that can be scaled to obtain rate of changes of the angles around x, y and z axis in [deg/s].[24]

In order to convert the ADC value into deg/s the following formula can be applied:

Equation 4.1 Conversion of the adc values into deg/s

$$\begin{aligned} \text{RateAxz} &= (\text{AdcGyroXZ} * \text{Vref} / 1023 - \text{VzeroRate}) / \text{Sensitivity} \\ \text{RateAyz} &= (\text{AdcGyroYZ} * \text{Vref} / 1023 - \text{VzeroRate}) / \text{Sensitivity} \end{aligned} \quad [25]$$

Where AdcGyroXZ, AdcGyroYZ – represent the ADC data showing rotation around Y and X axes respectively. Vref – is the ADC reference voltage. VzeroRate is the zero-rate voltage that is the voltage that the gyroscope outputs when it is not subject to any rotation. Sensitivity is the sensitivity of a gyroscope expressed in [mV / (deg / s)].

Equation 4.2 Scaling gyroscope output.

$$\begin{aligned} \text{gyro_x_scaled} &= \frac{d}{dt} \theta_x^{\text{gyro}} \\ \text{gyro_y_scaled} &= \frac{d}{dt} \theta_y^{\text{gyro}} \\ \text{gyro_z_scaled} &= \frac{d}{dt} \theta_z^{\text{gyro}} \end{aligned} \quad [19]$$

Accelerometer measures the force vector R projected over x, y, z axis that includes gravity. In order to get the force vector expressed in g from the ADC values the following formulas should be applied.

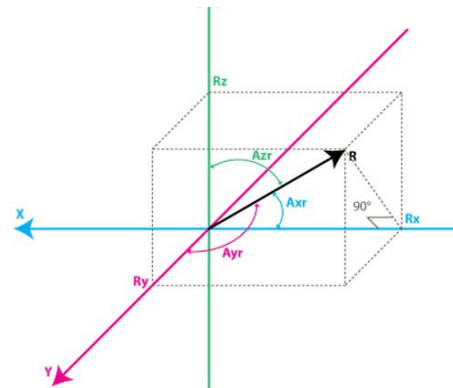
Equation 4.2 accelerometer adc values to Force vector [g] conversion

$$\begin{aligned} R_x &= (\text{AdcRx} * \text{Vref} / 1023 - \text{VzeroG}) / \text{Sensitivity} \\ R_y &= (\text{AdcRy} * \text{Vref} / 1023 - \text{VzeroG}) / \text{Sensitivity} \\ R_z &= (\text{AdcRz} * \text{Vref} / 1023 - \text{VzeroG}) / \text{Sensitivity}. \end{aligned} \quad [26]$$

VzeroG- zero-g voltage level, found in the datasheet. [29]. Sensitivity is the sensitivity of an accelerometer expressed in mV /g. Vref – is the ADC reference voltage. AdcRx is the raw ADC values.

Inclination of the accelerometer can be measure relative to gravity vector. The angles Axr, Ayr, Azr that are the angles between X,Y,Z axes and the force vector R can be measured with following formulas:

Figure 4.1 Acceleration vector



Equation 4.3 Inclination of the accelerometer relative to gravity vector estimation

$$A_{xr} = \arccos(R_x/R) ; A_{yr} = \arccos(R_y/R) ; A_{zr} = \arccos(R_z/R). [26]$$

IMU orientation estimation with application of sensor fusion algorithms

There are a number of steps that should be taken when combining accelerometer, gyroscope, magnetometer data together for orientation estimation. The details on the orientation estimation with each of the algorithms are not presented, however can be found in the reference literature sources.

1. Aline coordinate systems of accelerometer and gyroscope. Accelerometer can be used as a reference frame.
2. Calibrate gyroscope and accelerometer
3. Apply sensor fusion algorithm to determine orientation

Sensor fusion of the gyroscope, accelerometer and magnetometer for orientation estimation can be performed with a number of algorithms implemented in the software:

- Complementary filter;
- Kalman filter, Extended and Unscented Kalman (non-linear systems);
- Colton [SC];
- Premerlani and Bizard [PB];
- Starlino [St];
- Lauszus [La];
- Mahony [RM] and Madgwick [SM] [27]

As well as that there are a number of IMU platforms that include digital motion processing units that perform sensor fusion at the hardware level and give direct output in angles. Hardware sensor fusion significantly reduces load on the processor.

The comparison and the choice of the IMU sensor is presented in the research design chapter, because sensor calibration and speed, position tracking test procedure can be different depending on the sensor choice.

The table 4.1 in appendix presents comparison of platforms with built in dedicated sensor fusion embedded processor. During the research most of the sensors presented in the table 4.1 were tested.

As a result of comparison different IMU sensors BNO055 is chosen to be the best solution for the given application. BNO055 is the main sensor that has a 9 DOF sensor fusion. From the described sensors BNO055 is the only sensor that performs complete sensor fusion on board and gives direct output of linear acceleration for X, Y, Z axis with subtracted gravity. As well as that this chip can be purchase in the easy to interface break-out board. All the outlined advantages of BNO055 make it a good choice for the given application.

4.2.2 Position, velocity tracking with IMU. Background information

There are a number of steps that need to be taken in order to estimate velocity and position from the measured accelerometer data, they are:

- Sample data from the accelerometer with the defined time step
- Determine orientation of the force vector and rotate it back into the world reference frame.
- Subtract gravity vector.
- Integrate linear acceleration values a over the time δt to obtain velocity. $v(t)=v(0)+\sum a \times \delta t$
- Integrate velocity to get position. [28]

Equation 4.4 velocity from acceleration [28]

The main problem with obtaining velocity and position is drift over time due to integrated errors. The main source of errors are:

- Error in detecting orientation of the acceleration vector, therefore influence of gravity on linear acceleration estimations.
- Wrongly scaled sensor axes
- Zero offsets
- Temperature Influence
- Soft Iron and hard iron distortion errors of Magnetometer.[29]

Sensor Calibration

Accelerometer calibration

The simple way to calibrate accelerometer is to find minimum and maximum output values on each axis for the gravitation force by aligning each axis with the gravity vector, but moving accelerometer very slowly to minimize acceleration. After obtaining *zero-G* value and sensitivity from the datasheet a linear acceleration can be obtained after gravity vector is subtracted.

For a gyroscope calibration the following formulas can be applied:

$$\begin{aligned}x_{\text{calibrated}} &= (x_{\text{raw}} - ((\text{tempcomp}_x * \text{tempdelta}) + \text{offset}_x)) / \text{gain}_x \\y_{\text{calibrated}} &= (y_{\text{raw}} - ((\text{tempcomp}_y * \text{tempdelta}) + \text{offset}_y)) / \text{gain}_y \\z_{\text{calibrated}} &= (z_{\text{raw}} - ((\text{tempcomp}_z * \text{tempdelta}) + \text{offset}_z)) / \text{gain}_z \quad [25]\end{aligned}$$

Equation 4.5 Gyroscope calibration

Where temperature delta can be obtained with the temperature sensor, offsets for x, y and z can be obtained while keeping gyroscope still and averaging the readings. Gain and temperature compensation coefficients can be obtained from the datasheet.

Magnetometer calibration should include calibration for the *soft iron* and *hard iron* distortions that will be present in the operation environment. Compensating for *hard/soft iron* errors where the source of distortion external from the sensor and is changing over time is only possible to a certain degree and requires complex adaptive algorithms.

In order to answer second research sub-question the following steps are taken:

1. Theoretical calculation on possible accuracy of the IMU position tracking are presented.
2. The IMU sensor is chosen and orientation, position tracking program is implemented.
3. The accuracy of the orientation tracking is tested with the developed solution
4. The accuracy of the position tracking is tested and compared to the theoretical.

The amount of drift in inertial position tracking depends on the orientation error and as a result gravity compensation error when determining linear acceleration, accelerometer error and time period.

4.2.3 Calculations on speed and position accuracy

The theoretical velocity and position accuracy relative to the orientation error is determined in a following way:

1. It is assumed that IMU is stable and has an orientation of vector of $[0, 0, 9.81]$ for x, y, z axis expressed as an Euler angles in degrees.
2. The acceleration data when the IMU is stable is modeled, that is 0 m/s^2 for x and y axis and $9.81[\text{m/s}^2]$ for z axis sensing gravity.
3. The acceleration vector is multiplied by a rotation matrix with a chosen orientation error.
4. The gravity vector of $[0, 0, 9.81] \text{ m/s}^2$ for x, y, z axis is subtracted from the acceleration vector.
5. The resulting gravity compensated linear acceleration is integrated for a variable time frame to determine velocity and position drift.

As the result the conclusion on the linear acceleration, velocity and position error specifically due to orientation tracking error is made.

In order to conclude on the accelerometer error in the estimations the accelerometer data is modeled for the assumption that IMU has a constant acceleration and an accelerometer error is obtained from the datasheet of the BNO055 that is 1% of the given acceleration output. [29]

4.2.4 Testing IMU orientation tracking drift

The goal of the given test is to estimate the BNO055 orientation drift when the sensor is stable. The movement of the hair style is under 60 s (according to the product research center test visits). Sensor can be reset every time the motion is finished and hair-styler is open. However it is also interesting to track the orientation error after longer time periods. Time period of 30 minute is chosen, because it is long enough to cover the overall styling procedure.

To determine the error and amount of drift with BNO055 orientation tracking two set of tests were performed.

Test 1 was made with following steps:

- The BNO055 was calibrated. The sensor calibration is automatic and consist of rotating the sensor around X, Y and Z axis till the maximum calibration level is reached. The calibration level is obtained from reading the standard sensor register. The calibration routine and information on data registers can be found in the datasheet of the sensor [29].
- The BNO055 sensor was attached to a stable set up, to keep it fixed for the test period.
- The orientation data expressed in Euler angles [degrees/s] was logged for the time period of 60 s with a sampling frequency of 20 Hz.

- The orientation reading at the beginning of the test are compared to the orientation reading at the end of the test and as a result the amount of sensor drift after 1m is obtained.
- The test was performed for 10 times where sensor was recalibrated between each of the test.

Test 2 was performed following exactly the same steps, however the duration of the test was 30 minutes and number of performed tests was 5.

Depending on the result outcome the paired t- test could be performed to statistically conclude on the error. The desired power of the test would be 0.80, at significance level of 0.05 and would require hire sample size. However if the orientation error will be clearly low, there is no need to draw statistical conclusion from the 30 min test. Because it is preferred that the IMU sensor should be reset within 60 s during the hair-styling motion.

4.2.5 Testing IMU linear acceleration, velocity and position drift

The goal of the test is to determine accuracy of the velocity, position tracking for a certain time period with the IMU of choice.

- The BNO055 was calibrated as in the previous test based on the datasheet information [29]
- The BNO055 sensor was attached to a stable set up, to keep it fixed for the test period.
- Linear, gravity compensated acceleration expressed in $[m/s^2]$ for X, Y and Z axis was logged from the BNO055 data registers, with the sampling rate of 20 Hz for the time period of 1 minute. Data registers that need to be accessed are stated in the datasheet [29].

The test is performed for 100 times, where the sensor was recalibrated after every 10 tests. The test is designed in such a way that can allow to test the hypothesis that the calibration process doesn't have an influence on the linear acceleration error.

The ANOVA test with $F(9,90) = 1.985$ is used to test the hypothesis. The standard deviation is estimated as the indicator of variance of the data.

Based on the logged linear acceleration data, the velocity and position drift was estimated for different time periods, 1, 5, 10 seconds and 1 minute. The velocity and position drift is estimated with simple integration formulas presented in the previous part of the chapter. Formula can be also found in the literature reference. [34] The matlab file that was used to perform calculation can be found in the submitted project folder, *"BNO055_speed_pos_drift"*.

The test results are compared to the theoretical estimations that allows to answer the research sub-question.

4.2.3 Testing Accuracy of Kinect position and speed tracking

In order answer the given sub-question the following steps are taken:

1. Kinect accuracy of hand speed and position tracking is tested for high speed of movement 0.5 [m/s] and slow speed 0.05 [m/s]
2. Kinect accuracy of hand holding the device speed and position tracking is tested for high speed of movement 0.5 [m/s] and slow speed 0.05 [m/s]

Testing accuracy of the hand positon and speed tracking

In order to conclude on the accuracy of the speed tracking the following test procedure is used:

1. Hand is attached to the test equipment that can to move in X, Y axis with controlled distance and speed.
2. The movement consist of the forward and backward movement along X axis that is set to 19 cm. Only the forward movement is taken into an account and is set to the speed of 0.5 [m/s]. The hand position and velocity over X, Y, Z axis is tracked and logged with the frame rate of 30 fps. The data was logged with the developed program based on Microsoft Kinect development API, [33]
3. The position is estimated as peak to peak position change over X axis for every forward motion. The estimated position change is compared to the distance of the 19 cm. Speed is estimated as the average magnitude of the X, Y, Z velocity vector during the forward motion. The possible errors of the test equipment are ignored.

The desired power of the test would be 0.80 at the significance level 0.05.

Test 1. The hand positon and speed was tracked. The test included 40 forward motion iterations with the speed of the equipment set to 0.5 m/s.

Test 2. The hand positon and speed was tracked. The test included 12 forward motion iterations with the speed of the equipment set to 0.05 m/s.

Test 3. The hand positon and speed holding the device was tracked. The test included 20 forward motion iterations with the speed of the equipment set to 0.5 m/s.

Test 4. The hand positon and speed holding the device was tracked. The test included 12 forward motion iterations with the speed of the equipment set to 0.05 m/s.

The normalized standard deviation is estimated as the indicator of the spread of the measurement data.

The presented set of tests allow to answer all the formulated research question.

CHAPTER 5 - RESEARCH RESULTS

5.0 Introduction

In the following chapter results of the calculations and the test results described in the research design are presented. The conclusions based on the results will allow to answer the formulated research questions.

At the beginning of the chapter estimation on theoretically possible position and speed accuracy with inertial tracking are presented. After that results on the tests with the chosen IMU module (BNO055) are presented and compared to theoretically possible.

In next parts of the chapter the tests on accuracy of speed and position tracking with Microsoft Kinect are presented. At the final part of the chapter conclusions on inertial tracking and tracking with Microsoft Kinect are made.

5.1 Calculations on position tracking with IMU

First, modelled results for the gravity compensated acceleration, velocity and position drift depending on the orientation error are presented in the table 5.1. The mathematical steps taken in order to obtain the results are described in the research design and can be found in the attached "linAcc_drift.m" matlab file.

The table 5.1 shows the relation between the orientation errors, gravity compensated acceleration, velocity and position errors for different time periods of integration when the sensor is stable. As explained in previous chapters the amount of drift is dependent on the time of integration, therefore results for different time periods are shown in the table. The table 5.1 presents the influence of orientation error without effect of other possible error sources.

Table 5.1 Calculations on gravity compensated acceleration error, velocity and position drift for different tracking time periods only due to different orientation error.

Angle Error deg	Accel Error [m/s ²]	Velocity Error magnitude [m/s]@3s	Velocity Error magnitude [m/s]@5s	Velocity Error magnitude [m/s]@10s	Position Error magnitude [m]@1s	Position Error[m] magnitude @3s	Position Error magnitude [m]@5s	Position Error magnitude [m]@10s	Position Error magnitude [m]@60s
0.001	0.0017	0.0052	0.0087	0.0175	0.00012	0.0079	0.0219	0.0879	3.1506
0.01	0.0030	0.0089	0.0149	0.0298	0.0012	0.0134	0.0372	0.1496	5.3630
0.06	0.0145	0.0436	0.0726	0.1453	0.0073	0.0655	0.1810	0.7267	26.152
0.1	0.0243	0.0728	0.1214	0.2427	0.0122	0.1094	0.3037	1.2198	43.730
0.5	0.1211	0.3632	0.6054	1.2107	0.0608	0.5455	1.5146	6.0839	218.11
1.0	0.2421	0.7264	1.2107	2.4214	0.1215	1.0911	3.0571	12.167	436.22
1.5	0.3632	1.0895	1.8135	3.6315	0.1823	1.6363	4.5848	18.248	654.21
2.0	0.4842	1.4525	2.4208	4.8415	0.2430	2.1815	6.1125	24.328	872.20
2.5	0.6051	1.8154	2.9712	6.0512	0.3038	2.7266	7.6397	30.407	1090.1
5.0	1.2092	3.6276	6.0461	12.092	0.6069	5.4486	15.263	60.763	2178.4

From the results it is clear that the speed and position tracking for time periods longer than 1s requires very high orientation tracking accuracy. For example, position drift after 10s is already 14.96 cm, when the accuracy is 0.01 degrees.

The obtained results can be compared with the literature reference.[34] It is important to notice that in the given literature source the main steps of calculations are explained, however exact procedure of obtaining the results is not given. As a result it is difficult to find the reason for a difference in results.

Table 5.2 Estimated errors for linear acceleration, velocity and position when sensor is stable. From the literature source. [35]

Table 5.2 Calculation from the literature source on linear acceleration, velocity, and position errors that can be expected given different errors in the orientation estimate of the sensor. [35] CHrobotcis

Angle Error (degrees)	Acceleration Error (m/s/s)	Velocity Error (m/s) at 10 seconds	Position Error (m) at 10 seconds	Position Error (m) at 1 minute	Position Error (m) at 10 minutes	Position Error (m) at 1 hour
0.1	0.017	0.17	1.7	61.2	6120	220 e 3
0.5	0.086	0.86	8.6	309.6	30960	1.1 e 6
1.0	0.17	1.7	17	612	61200	2.2 e 6
1.5	0.256	2.56	25.6	921.6	92160	3.3 e 6
2.0	0.342	3.42	34.2	1231.2	123120	4.4 e 6
3.0	0.513	5.13	51.3	1846.8	184680	6.6 e 6
5.0	0.854	8.54	85.4	3074.4	307440	11 e 6

The estimation results from the reference are different, but values are on the same scale, and very similar conclusions can be drawn.

Although orientation error has one of the highest impacts, the sensor errors also have an influence.

The results presented in the table 5.3 take into an account the accelerometer errors. As presented in the research design chapter there are a number of accelerometer error sources, such as sensitivity errors, zero-g offset temperature and supply voltage drift, nonlinearity. [29]. All the errors of the sensors that are integrated in BNO055 are obtained from the datasheet [30] and also summarized in the "modelled_errors.xlsx" excel file. The modelled data takes into an account only the sensitivity error that is 1% of the accelerometer output, with an assumption that the sensor is not stable, but moving with a constant speed of 0.1 [m/s].

Table 5.3 Calculations on gravity compensated acceleration error, velocity, position drift for different tracking time periods due to orientation error when accelerometer error is taken into an account.

Angle Error deg	Accelerator Error [m/s ²]	Velocity Error magnitude [m/s]@3s	Velocity Error magnitude [m/s]@5s	Velocity Error magnitude [m/s]@10s	Position Error magnitude [m]@1s	Position Error[m] magnitude @3s	Position Error magnitude [m]@5s	Position Error magnitude [m]@10s	Position Error magnitude [m]@1m
0.001	0.0222	0.0667	0.1110	0.2220	0.0111	0.0998	0.2777	1.1104	39.961
0.01	0.0232	0.0695	0.1159	0.2317	0.0116	0.1044	0.2899	1.1591	41.715
0.06	0.0303	0.0909	0.1514	0.3029	0.0152	0.1365	0.3789	1.5149	54.520
0.1	0.0379	0.1136	0.1893	0.3786	0.0190	0.1219	0.4736	1.8937	68.149
0.5	0.1158	0.3730	0.5790	2.3586	0.0581	0.5857	1.4486	11.797	208.45
1.0	0.2506	0.7517	1.2529	2.5057	0.1258	1.1290	3.1346	12.533	451.05
1.5	0.3715	1.1145	1.8575	3.7150	0.1865	1.6739	4.6474	18.582	668.74
2.0	0.4925	1.4776	2.4627	4.9254	0.2472	2.2193	6.1616	24.638	886.63
2.5	0.5983	1.8160	2.9916	5.9808	0.3003	2.6959	7.4847	29.972	10770
5.0	1.2183	3.6548	6.0914	12.182	0.6115	5.4894	15.26	60.937	2193.0

From comparing the tables 5.1 and 5.3 it can be concluded that accelerometer errors have a lower effect than the orientation tracking errors, however also should be taken in to an account. The difference is very clear.

5.2 IMU tracking test results

5.2.1 Orientation Tracking Test

In this part of the chapter results on tests performed with the chosen IMU sensor are presented.

All the tests are made with the BNO055 sensor that performs 9DoF sensor fusion. The choice of the BNO055 and comparison to other sensors is presented in the research design chapter and the table 4.1 in appendix.

A number of test with BNO055 were performed in order to determine orientation drift with time.

The BNO055 sensor fusion algorithm includes sensor calibration that is constantly updating the sensor calibration matrixes when the sensor is powered and system calibration registers are enabled. The BNO055 gives an output on the calibration level from 0 (not calibrated) to 3 (highest calibration level) for accelerometer, gyroscope, magnetometer and overall system with a maximum frequency of 100Hz [30]. The orientation tests were performed when the system is fully calibrated to the maximum level.

First, 10 test were performed when the orientation of the sensor were logged for the time period of 1m. Where the sensor was stable and recalibrated to the maximum level between each test. From the logged data it can be concluded that there is no orientation drift detected within 1m when the sensor is stable. The resolution of the obtained orientation with BNO055 is 0.06 degrees. Therefore the orientation error is lower than 0.06 degrees.

Second, 5 tests were made when the orientation of the sensor were logged for the time period of 30 min. Tracking velocity and position for 30 min is not feasible, based on the estimations. However there is an interest to check the performance of the sensor fusion algorithm integrated in the BNO055.

The following table shows the starting orientation vector obtained from BNO055 sensor and the orientation vector after 30 min, when the sensor was fixed. The estimated change in the orientation vector allow to conclude on the orientation tracking errors.

Table 5.4 Results for orientation tracking change during 30 minute tests, when the sensor is stable and not moving.

Tes t	Orientation X Y Z [deg] start			Orientation X Y Z [deg] after 30 min			X Y Z [deg] change		
1	210.5625	11.8125	43.8750	210.6225	11.8125	43.8750	0.06	0	0
2	177.3125	17.0625	3.1875	177.3125	17.0625	3.1875	0	0	0
3	254.5000	-2.2500	137.1875	254.5000	-2.2500	137.1875	0	0	0
4	207.5000	55.9375	159.0625	207.5000	55.9375	159.0625	0	0	0
5	212.2500	55.4375	160.1250	212.2500	56.6375	160.1250	0	0.12	0

Based on this test it is not possible to draw statistical conclusions, however it is clear that the sensor fusion algorithms is effective in compensating for the orientation drift.

5.2.2 IMU linear acceleration, velocity, position test

The ideal linear acceleration obtained from the sensor that is not moving should be 0 [m/s²] for x, y and z axis. Due to orientation and accelerometer errors, the gravity is not fully compensated that results in linear acceleration error, velocity and position drift when the linear acceleration is integrated.

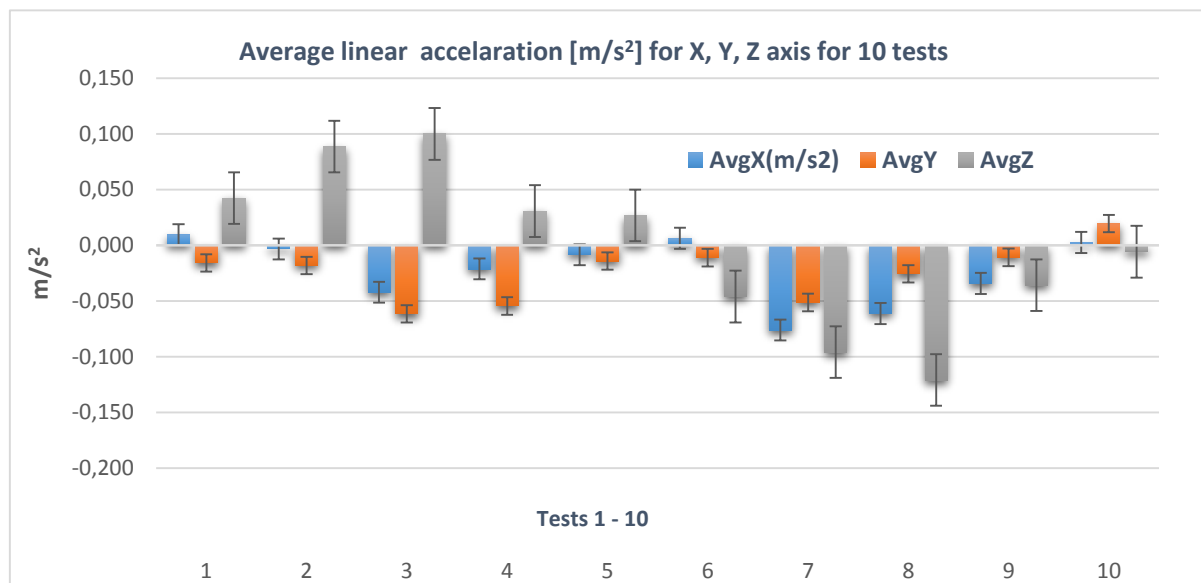
The following test is performed to show the linear acceleration error obtained from the BNO055.

The 10 tests were made that logged linear acceleration when the device is stable. Between each of the tests the sensor is recalibrated to the maximum calibration level. Within each of the 10 tests, the linear acceleration is logged for 5 seconds, with 20Hz sampling rate, 10 times, where the sensor is not recalibrated. The velocity and position drifts are calculated for each of the tests.

The following graph shows the acceleration after gravity compensation obtained from BNO055 that ideally should be 0 m/s² if orientation tracking would be errorless and there would be no sensor measurement errors.

In total there were 100 tests when the average linear acceleration for X, Y, Z axis was logged while sensor is fixed. The sensor was recalibrated after every 10 tests. Therefore the tests can be grouped in 10 sets and the figure 5.1 graph shows the average linear acceleration for every group of the 10 tests. The standard error bar is shown in figure 5.1 for each of the test and is the indicator of the sensor output variation.

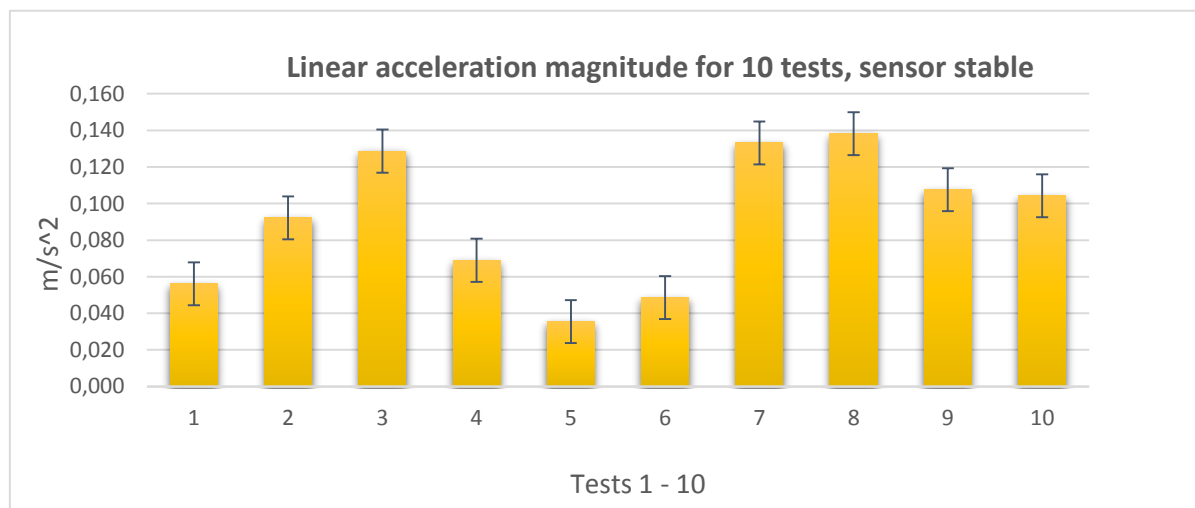
Figure 5.1 Average linear acceleration for X, Y, Z axis over 10 tests, sensor stable and recalibrated.



The difference in acceleration values between X, Y and Z axis can be explained by the different orientation of the sensor between tests.

The next graph shows the average linear acceleration for each of the 10 test sets when the sensor is stable and recalibrated between each of the test sets. There are 10 tests within each of the test set, therefore the standard deviation can be estimated over 100 tests. The results are presented in the table 5.5.

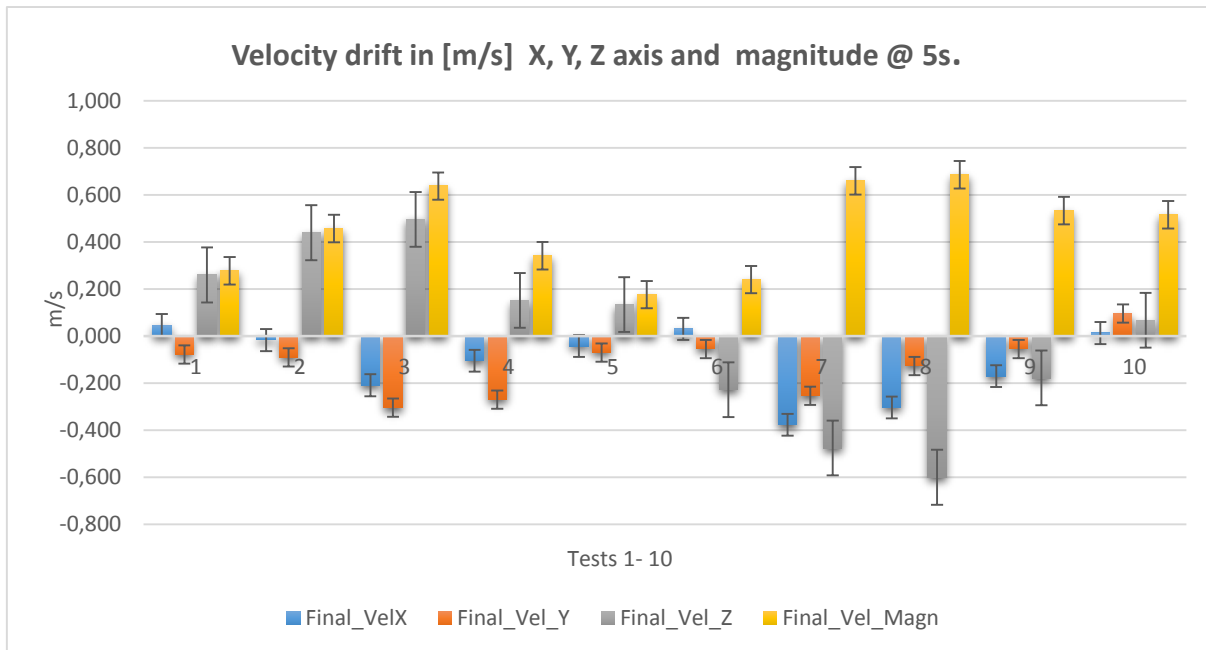
Figure 5.2 Average linear acceleration magnitude over performed 10 tests and overall 100 test samples.



The sensor was recalibrated between each test to the maximum level. The graph shows that the sensor performs differently between recalibrations

The following figure shows the velocity vector and velocity magnitude estimated from the obtained linear acceleration during the same 10 sets of tests.

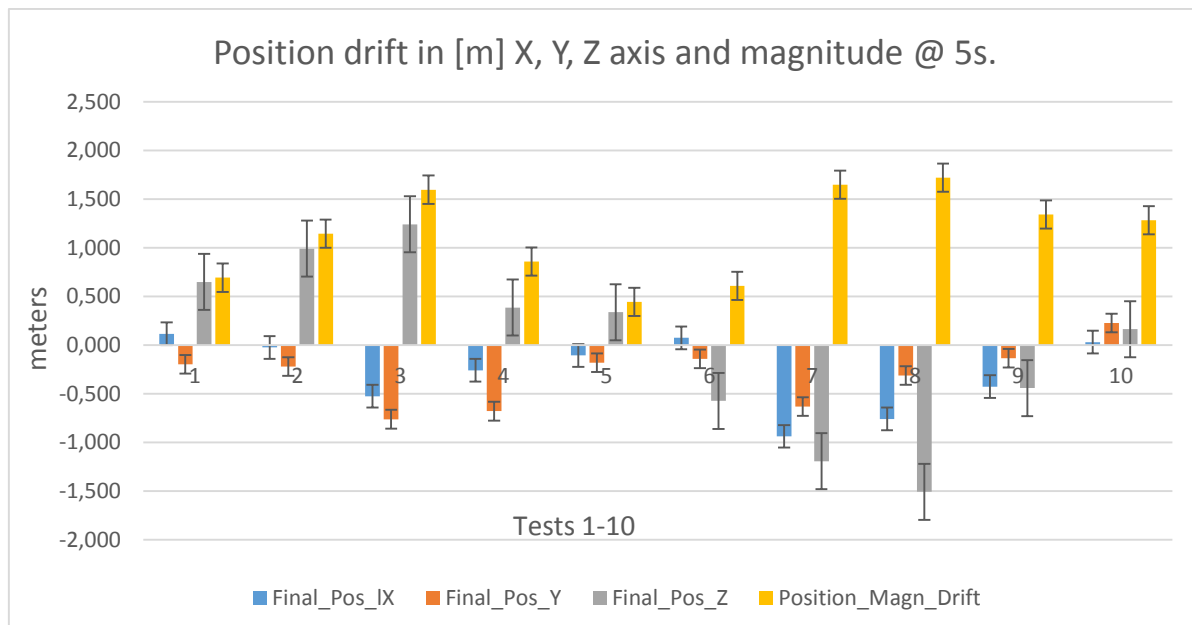
Figure 5.3 Velocity drift for X, Y, Z axis and velocity vector magnitude after 5 seconds when the sensor was stable.



Velocity drift magnitude is proportional to the acceleration error. From the results it can be seen that the lowest velocity drift is 0.176 [m/s] while the highest drift is 0.68 [m/s]. It can be noticed that the standard error for the acceleration and velocity is higher for Z axis comparing to Y and X axis, this is expected due to gravity compensation on the Z axis.

The following figure shows the position vector and position magnitude estimated from the obtained linear acceleration during the same 10 sets of tests.

Figure 5.4 Position drift for X, Y, Z axis and magnitude after 5 seconds



The position is obtained as a double integrated linear acceleration and from the graph it can be seen that the position drift is relative to the acceleration error, but with a higher scaled difference between tests.

The next table shows the overall results, where the average values for gravity compensated acceleration, velocity and position for each of the 10 test sets are presented. Standard deviation for overall 100 tests.

Table 5.5 Summarised test results for position and velocity drift after 5 seconds when the sensor is stable.

Test	Acceleration Magnitude [m/s ²]	Speed magnitude drift [m/s] @5 s	Position magnitude drift [m] @ 5 s
1	0,056	0,278	0,692
2	0,092	0,457	1,144
3	0,129	0,637	1,596
4	0,069	0,341	0,858
5	0,035	0,176	0,443
6	0,049	0,240	0,608
7	0,133	0,659	1,648
8	0,138	0,685	1,720
9	0,108	0,533	1,341
10	0,104	0,516	1,282
Mean	0,091	0,452	1,133
STDEV 100 tests	0,042	0,215	0,523

Table 5.6 Summarised test results for position and velocity drift after 1 second

Test	Acceleration Magnitude [m/s^2]	Velocity drift [m/s] @1 s	Position drift [m] @ 1 s
1	0,056	0,0532	0,0266
2	0,092	0,0874	0,0437
3	0,129	0,1225	0,0613
4	0,069	0,0656	0,0328
5	0,035	0,0333	0,0166
6	0,049	0,0466	0,0233
7	0,133	0,1264	0,0632
8	0,138	0,1311	0,0656
9	0,108	0,1026	0,0513
10	0,104	0,0988	0,0494
	0,091	0,0864	0,0432
STDEV over 100 tests	0,042	0,0307	0,0165

From the tests it is concluded that an average position error is 1.133 m with a standard deviation of 0.43 m after 5 seconds.

The orientation error of the BNO055 is lower than 0.06 degrees and position drift would be much lower if there would be no acceleration errors that can be seen from the presented estimations.

From this it can be concluded that there is a difference between orientation errors, but the variation is within 0.06 degrees and therefore not detected. As well as that accelerometer error can have a high variance.

The ANOVA test was performed in order to check the influence on the sensor calibration on the linear acceleration error at the probability level $p = 0.05$. One way ANOVA test is made using excel that is usually used to test if means of a number of populations are equal.

Table 5.6.1 one- way ANOVA results

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0,015511222	9	0,001723469	0,954244573	0,483073	1,985595
Within Groups	0,162549756	90	0,001806108			
Total	0,178060978	99				

SS between groups is much lower than SS within group, $F < F$ critical, therefore the null hypothesis is accepted and it can be concluded that calibration error doesn't have influence on the linear acceleration error.

5.2.3 IMU tracking conclusions

The performed theoretical estimation and test results show that speed and position tracking for hair styling appliances with currently available low-cost inertial sensors such as BNO055 is not feasible even for time periods under 10s. At the same time orientation tracking is tested to be accurate and stable with accuracy of higher than 0.06 degrees. The velocity and position drift obtained from the test result is higher than expected from the theoretical estimations. For the orientation tracking error of 0.06 degrees the position drift after 1 s was estimated to be 1.52 cm, whereas the tests with BNO055 showed the average position drift of 4.32 cm with the standard deviation of 1.65 cm. The lowest position drift obtained from the test was 1.66 cm that is closer to estimated error. The difference between theoretical estimations and tests shows that the accelerometer errors are higher than sensor errors that are taken into an account in calculations. Sensor calibration errors are also not taken into an account in estimations with modeled data.

Currently inertial sensors are being developed and improved rapidly. The performed research and tests are important because they allow to understand what accuracy of position and speed tracking can be achieved with given sensors.

5.3 Speed tracking accuracy test with Kinect

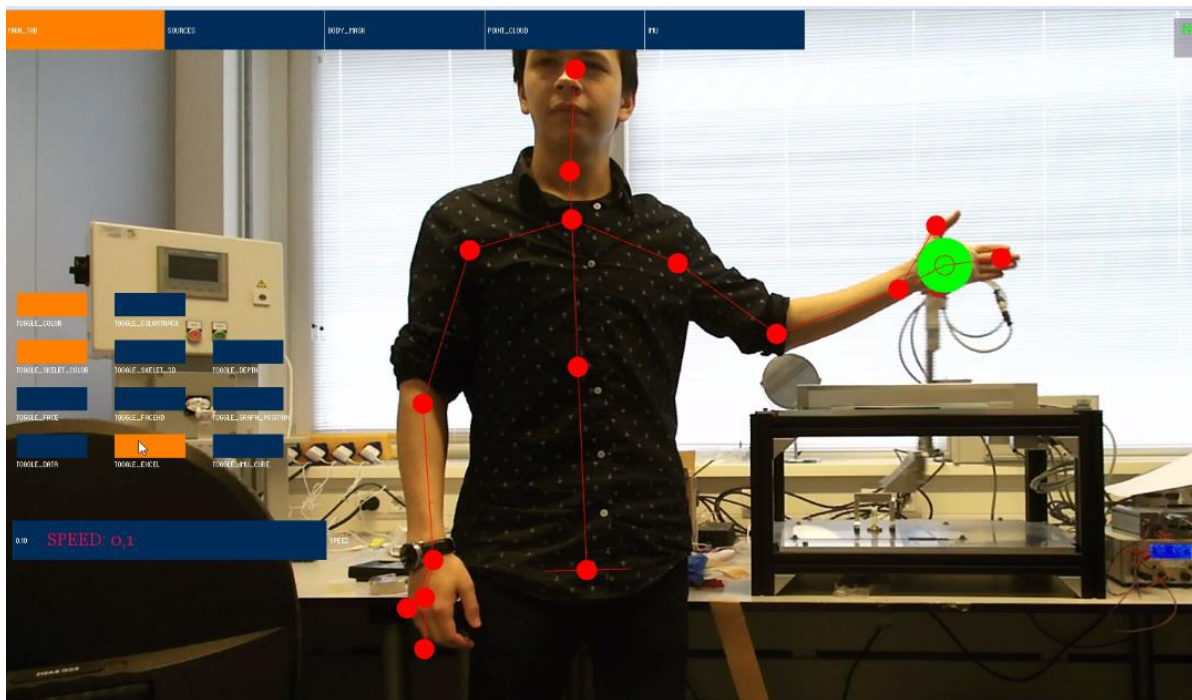
5.3.1 Tracking speed of the hand without an appliance

The goal of designed and performed test was to determine the accuracy of hand tracking with Microsoft Kinect.

The setup that can move in X, Y plane with a controllable speed and position was used. The hand was attached to the setup and the movement of the hand was tracked with Microsoft Kinect. The results were compared in order to determine the accuracy of the Kinect hand tracking relative to the equipment as a reference.

Ten tests were performed where position change in X, Y, Z directions were logged and the speed vector and magnitude were estimated.

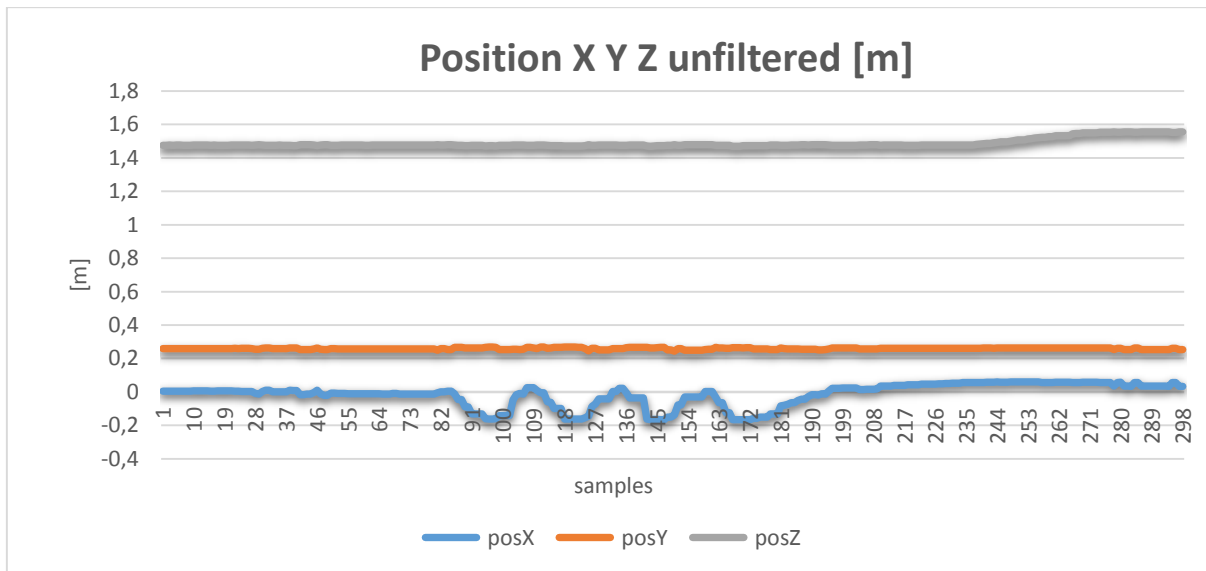
Figure 5.5 Test set up that was used for testing the accuracy of hand tracking.



Each of the 10 performed tests consisted of 4 iterations of linear motion in X axis with the set speed of 0.5 [m/s] for forward movement the distance of 19.0 mm. The backward movement is ignored in all of the tests.

The measurements recorded with Microsoft Kinect for one test are presented in the following graphs.

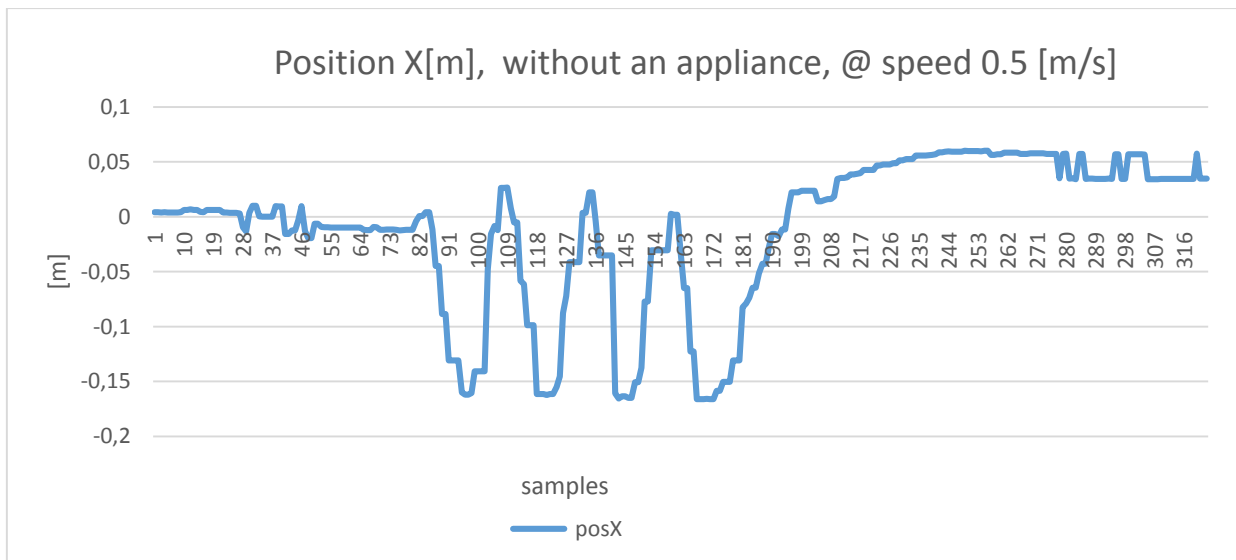
Figure 5.6 Position tracking results of one out of 10 performed tests that included 4 motion iterations in x axis.



The given graph shows that the movement over X axis is clearly detected and Y and Z axis are stable that was expected.

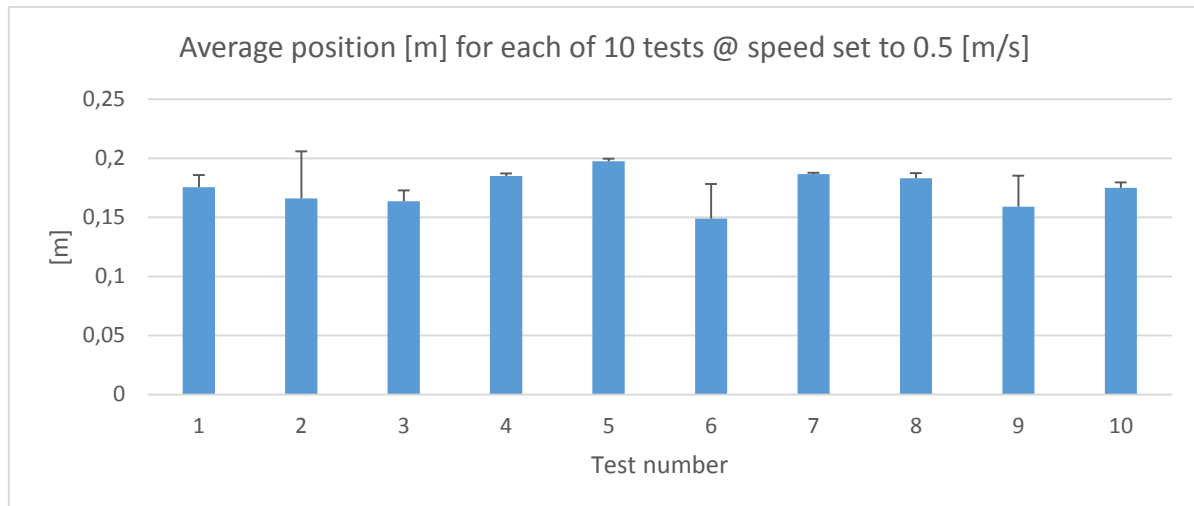
The next graph shows measured position over X axis from one out of 10 performed tests.

Figure 5.7 Position tracking results of one out of 10 performed tests showing measured position change over x axis.



The tests results over 10 tests with 4 movement iteration within each of the test are presented in the following graph. The position change is estimated as peak to peak values.

Figure 5.8 Average tracked position for each of the 10 tests estimated as peak to peak values.

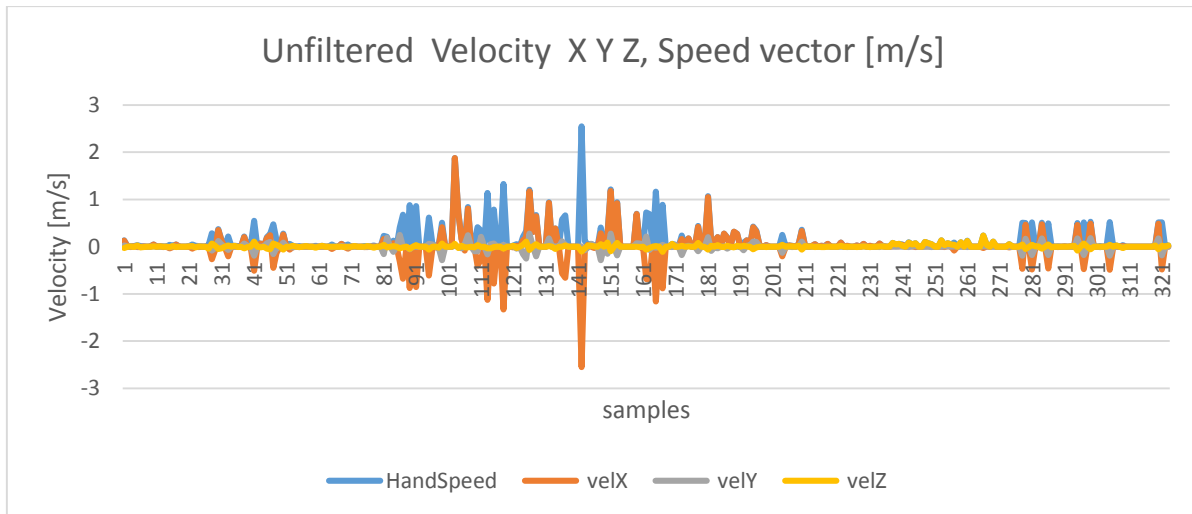


From the test results it can be conclude that the average measured distance over 40 tests is 0,174 [m], while the set up was set to move for 0.190 [m]. The estimated standard deviation between the 40 tests is 0.0139 [m]. It can be expected that one of the sources of error resulting in variation between tests is a change of frame rate, therefore another set of tests will be presented to confirm that variation is not due to the frame rate change. Graphs for each of the test are not presented in the report, but by analysing the data, it can be observed that in tests 6 and 9 where the standard deviation is high, one of the 4 position change peaks is not detected due to sample loss.

After discarding tests 6 and 9 the average measured distance is 0,174 m and an average error of 0.016 [m/s] is therefore and a standard deviation is 0.0139 [m].

The next graphs presents estimated unfiltered velocity of the tracked hand without an appliance for X, Y and Z axis.

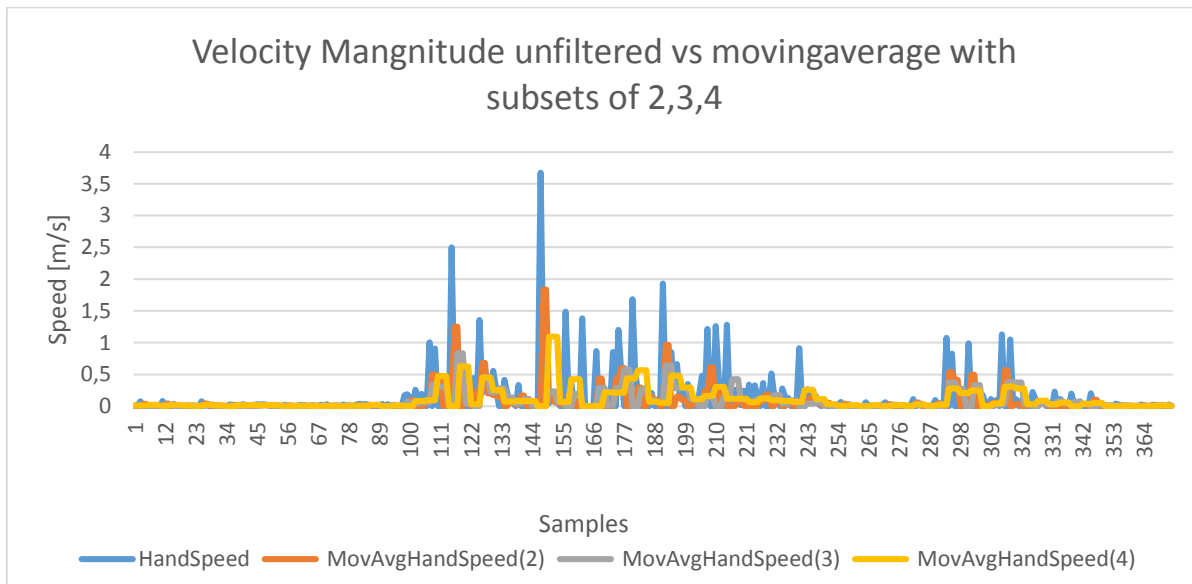
Figure 5.9 shows the unfiltered results of speed tracking for one of the 10 performed tests



From the given graph it is clear that there is motion detected on the X axis, while speed estimated over Y and Z axis is close to zero.

Moving average filters with subsets size of 2, 3, and 4 are tested and compared. The next figure shows the results of speed tracking during the test when the test equipment was set to move for 19 cm with the speed of 0.5 [m/s] for forward movement. Within the test there were 4 movement iterations. The effectiveness of the filter is estimated by comparing the resulting average speed during the forward movement for 19 cm after filtering with the reference 0.5 m/s.

Figure 5.10 Comparison of moving average performance with sample subsets of 2, 3 and 4.

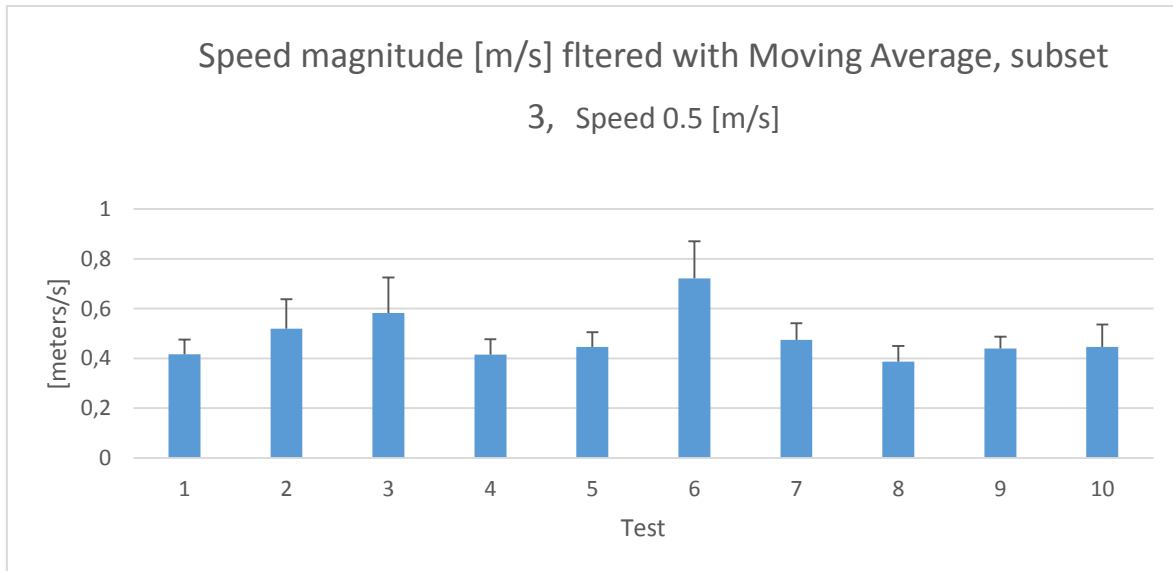


Comparing the estimated average speed only during the forward movement from the performed test that included 4 movement iterations, the accuracy of moving average filter with subset 3 showed the closest values to the 0.5 m/s where the error was 0.0188 [m/s], while the error with unfiltered data was estimated to be 0.12 [m/s], and the error for moving average with subsets 2 and 4 was 0.07[m/s] and -0.09 respectively.

The next set of graphs will show the test results.

The following graph presents the tracked velocity over performed 10 tests with 4 movement iterations within each test at speed of the test equipment set to 0.5 [m/s]. Speed magnitude of the tracked hand is estimated as an average speed over the duration of the forward motion for every forward movement. The test includes 40 forward movement in total. The speed magnitude is filtered with the moving average filter of subset 3. Standard error bar shows the measurement variation within each group of the tests.

Figure 5.13 Speed magnitude of the tracked hand, speed of test equipment set to 0.5 [m/s]



The average speed estimated over 40 tests after filtering is 0,484 [m/s] and an average error of 0,016 [m/s] with a standard deviation of 0.152 [m/s] between tests.

At the same time the average unfiltered speed over 40 tests is 0,954 [m/s] with a standard deviation of 0,3257 [m/s]. Such a high average speed is the result of high peak jumps.

The tests 6 and 9 had a lower frame rate than normal, therefore discarding this two test the average filtered speed is 0,425 [m/s] and an average error of 0.075 [m/s] with a standard deviation of 0.011 [m/s] between tests.

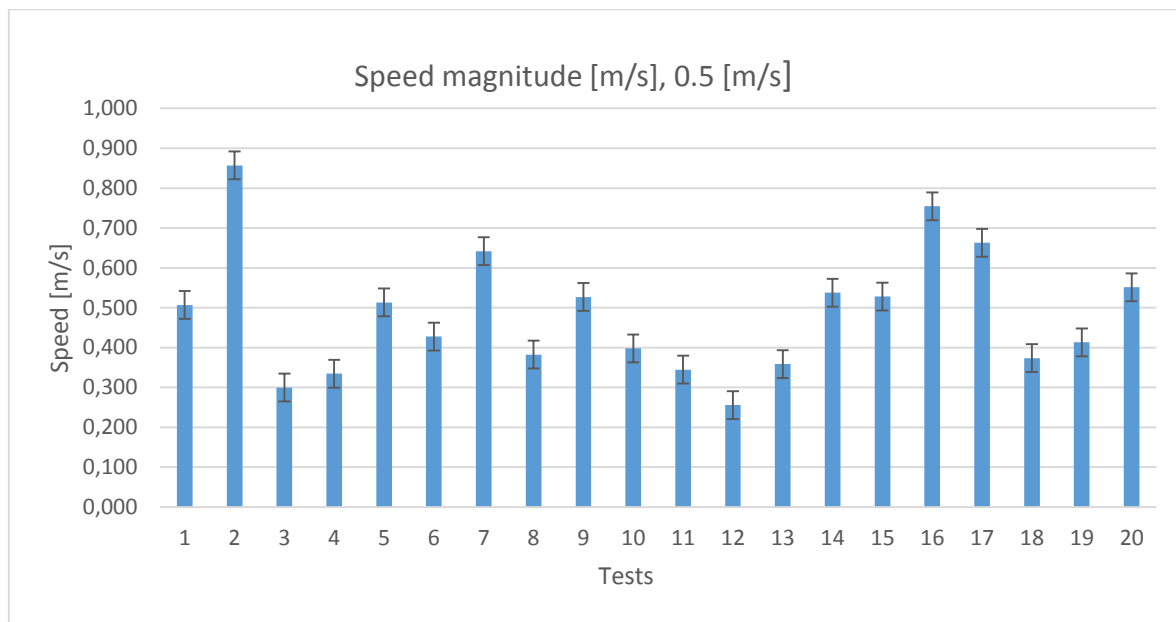
In order to eliminate the influence of the frame rate on the speed tracking accuracy, a second set of the same tests was performed when the frame rate was more stable, close to maximum 30 fps.

In the next set of tests only speed tracking accuracy is estimated and presented, because from the previous test position tracking with Kinect software showed accurate results and peak to peak position estimation is not very sensitive to the sensor noise.

5 tests were made where there were 4 linear motion iterations in X axis within each of the test, resulting in 20 motion iterations in total. The test equipment was set to move for the distance of 19 [cm] with the speed of 0.5 [m/s]. The hand was attached to the test equipment and position and velocity was logged real time with developed software for Microsoft Kinect.

The following graph represent the average speed for the duration of forward motion set to 0.5 [m/s] estimated with the Kinect software.

Figure 5.14 Speed magnitude over 20 motion iterations. Test equipment set to the speed of 0.5 [m/s], moving average filter with subset 3 is applied.



Comparing the tracked speed to the reference of 0.5 [m/s] it is calculated that an average error of tracked speed over the 20 test is 0,037 [m/s] with a standard deviation of 0,126 [m/s].

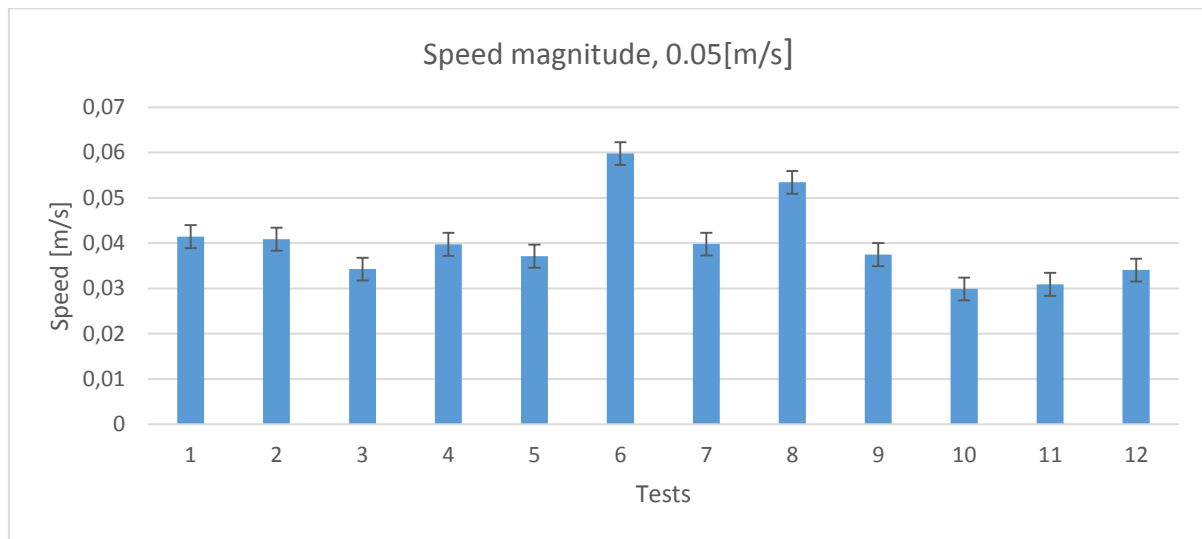
Very similar results were obtained from the second test, however with a much higher standard deviation. As the result of the test we are sure that the first set of tests were not very influenced by a less stable frame rate.

As one of the recommendations for the future of the project would be to research on solutions that would allow to create software with a very stable framerate, as long as lighting conditions and processing power of the computer are not changing.

The next set of tests were performed with the test equipment set to move with a speed of 0.05 [m/s] for the distance of 19 [cm]. The test included 12 forward motions where as in previous tests the average speed recorded with the Kinect software during the motion was compared to the reference 0.05 [m/s]

The next chart shows the average speed recorded for every forward motion and filtered with moving average filter with subset of 3 samples.

Figure 5.15 Speed magnitude of the tracked hand over 12 motion iterations, speed set to [0.05 m/s], after moving average filter, subset 3.



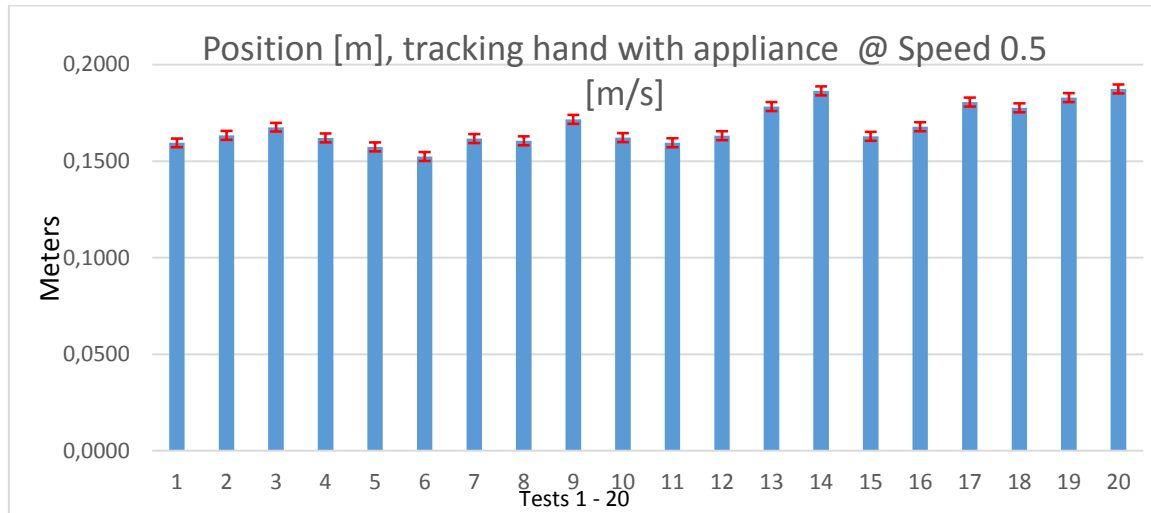
The resulting average error over 12 motion samples is 0,009 [m/s] with a standard deviation of 0,008 [m/s]

5.3.2 Tracking speed of the hand with an appliance

The set of tests were made in order to conclude on the accuracy of Kinect hand tracking when holding the hair-styling appliance. Exactly the same test procedure were used as in the tests presented above.

The following chart shows the results obtained from the Kinect for estimated peak to peak position change over the X axis, when the test equipment was set to move for 19 cm with the speed of 0.5 [m/s].

Figure 5.16 Positon change over X axis of tracked hand holding the device over 20 motion iterations, the test equipment speed set to of 0.05 [m/s]. Movement length 19 cm.



From the test results the average position error is calculated to be 2.17 [cm] with a standard deviation of 1.101 [cm]. From this test it is clear that holding the device doesn't influence peak to peak position change estimation.

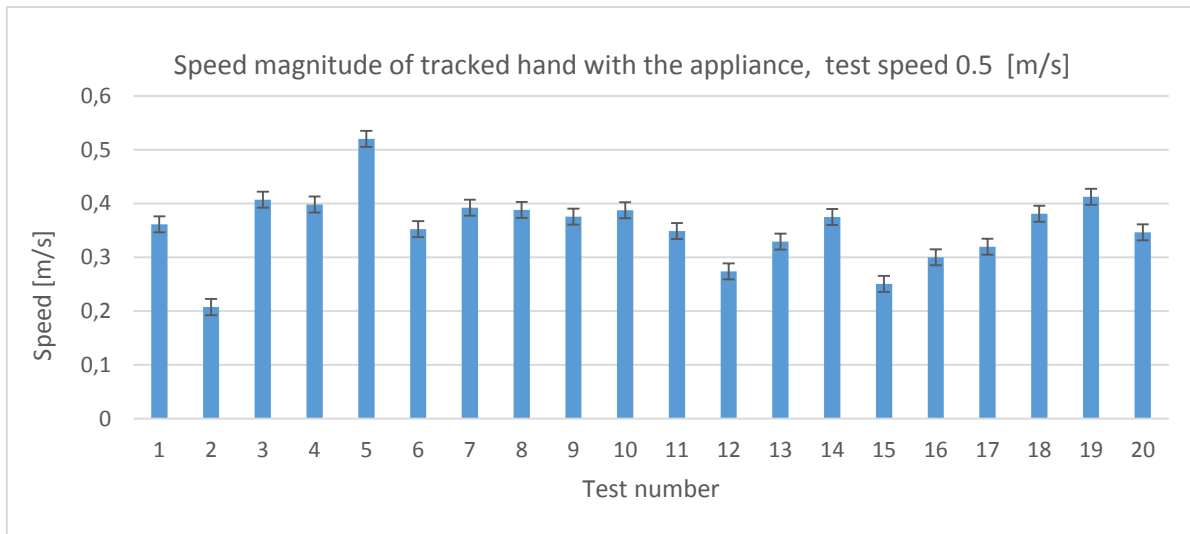
The same set of tests was performed with the test equipment set to move for 19 [cm] with the speed of 0.05 [m/s]. The estimated error of position tracking over 12 tests is 2.20 [cm] with the standard deviation of 2.37 [cm].

The next step of the test are made to conclude on the accuracy of the speed tracking with Kinect software when holding the appliance.

The next figure shows the estimated speed of the tracked hand with holding the appliance for when the test equipment is set to move for 19 [cm] with the speed of 0.5 [m/s] for the forward motion.

Speed magnitude of the tracked hand with the appliance over 20 motion iterations estimated with Kinect software, when the test equipment was set to move with the speed of 0.5 [m/s]. The speed is calculated as an average speed over the duration of the forward motion. The speed magnitude is filtered with the moving average filter of subset 3.

Figure 5.17 Average speed magnitude for 20 motion iterations.



The resulting average speed error over 20 motion samples is estimated to be 0.145 [m/s] with a standard deviation of 0.0608 [m/s].

The same test was performed with the test equipment set to move with the speed of 0.05 [m/s].

It is important to mention that the highest influence on the accuracy of speed tracking plays accurate detection of the hand by the Kinect tracking algorithm. When holding the device the hand detection is not always stable and estimated position can jump between the hand and the device, resulting in a lot of position change noise that has a great impact on the speed tracking. In the previous test when holding the device at the test equipment set to the speed of 0.5 [m/s] the hand was detected accurately by the Kinect algorithm and there was not a lot of position jumps. The test that is presented next with the test equipment set to the speed of 0.05 [m/s] showed that accurate hand detection when holding the device can be a problem. In the following tests hand tracking included a lot of short distance jumps between the hand and the device that resulted in a much lower accuracy of speed tracking.

The next two figures show a velocity of the tracked hand with the device over X vector axis, during the set of tests with set speed of 0.5 [m/s] and speed of 0.05 [m/s]. The test equipment had 4 forward and backward motion iterations with the controlled forward motion. The backward motion wasn't taken into an account.

Figure 5.18 Unfiltered velocity over X axis tracked hand with the appliance. 4 forward and backward motion iterations, the test equipment speed - 0.5 [m/s].

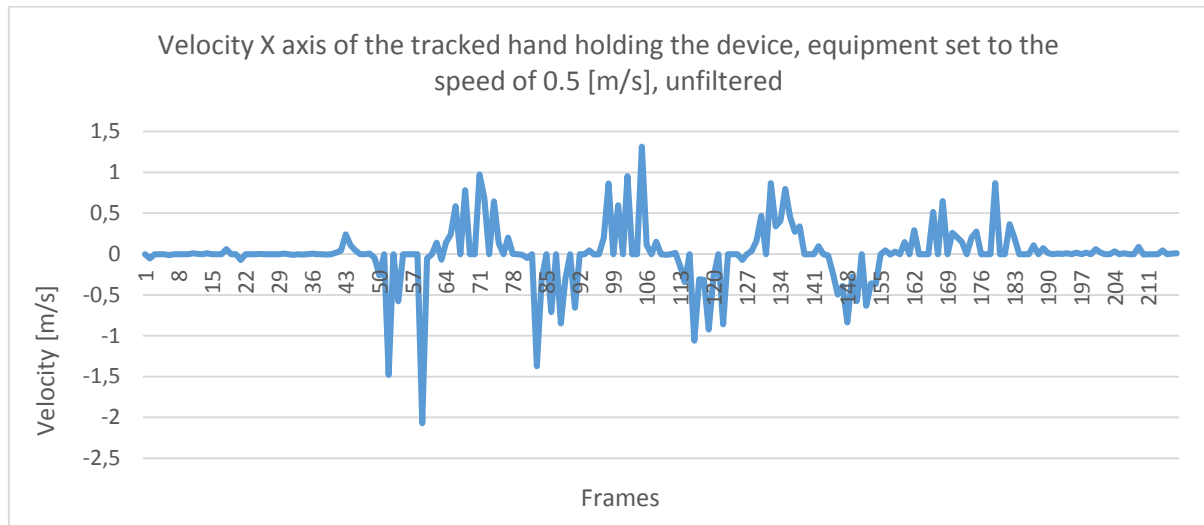
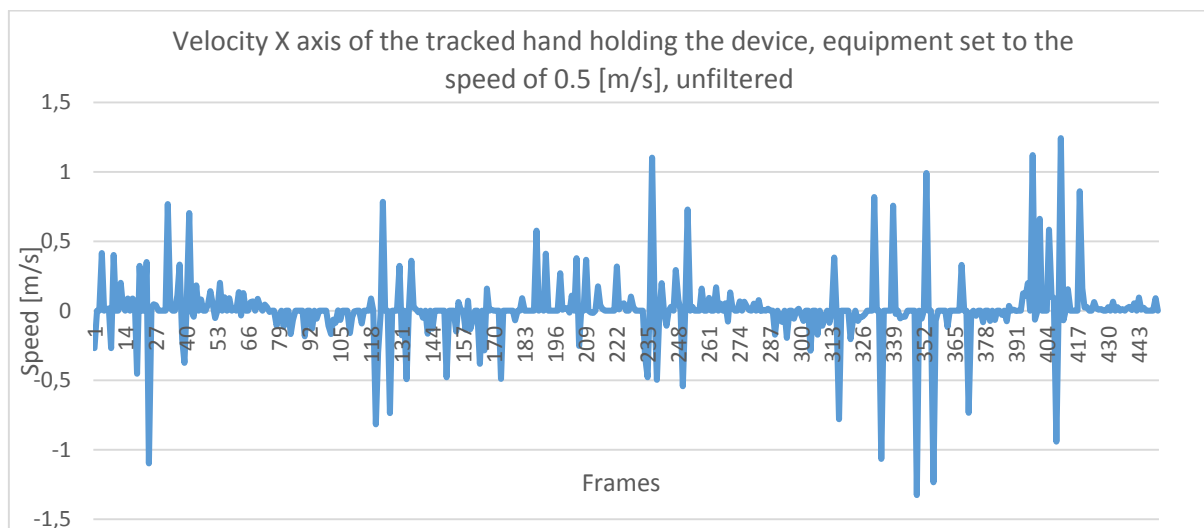


Figure 5.19 Unfiltered velocity over X axis of the tracked hand with the appliance, 4 forward and backward motion iterations, test equipment set to the speed of 0.05 [m/s].



Analysing the figure 5.18 it is clear that the velocities for forward and backward movements are clearly detected and separated. The previously discussed tests showed similar results for 20 tests where hand was tracked accurately and there was no position tracking jumps between the hand and the appliance.

The figure 5.19 shows the results from the same tests, but with the speed set to 0.05 [m/s]. Looking at the velocity over X axis it is clear that there is a lot of forward and backward velocity changes over the X axis that is the result of position jumps between the hand and the appliance. Absolutely this errors in separation between hand and appliance have a great influence on the speed tracking accuracy.

In the case of the test estimating speed as the magnitude clearly results in a very not accurate speed magnitude due to additional change in position caused by errors in separation between hand and the appliance. Estimating the speed only over the negative values of the X axis velocity that indicates only the forward movement should result in a relatively small speed error. The resulting average error over 12 tests is 0,004 [m/s] with the standard deviation of 0,011 [m/s]. The resulting error is low with a relatively low standard deviation. However normally during the test the direction of motion is not known and the speed magnitude over all x, y and z axis are estimated.

5.3.3 Discussion and conclusion on position and speed tracking accuracy with Kinect

A number of tests were performed in order to check the accuracy of hand position and speed tracking with Microsoft Kinect at the speeds of movement controlled by the test equipment and set to 0.5 [m/s] and 0.05 [m/s]. The errors of speed and position tracking were estimated for the hand joint tracking and tracking hand holding the device.

The following table summarises the main test results.

Table 5.7 Summarized test results performed with Microsoft Kinect speed and position tracking.

Tests	Position error @ 0.5 [m/s]			Speed error @ 0.5 [m/s]			Speed error @ 0.05 [m/s]		
	Number of tests	Error[m]	STDEV	Number of tests	Error[m/s]	STDEV	Number of tests	Error[m/s]	STDEV
Hand	40	0.016	0.0139	40	0.075	0.011	12	0.009	0.008
				20	0.037	0.126			
Hand with appliance	20	0.022	0.0101	20	0.145	0.061	Very high error. When errors in hand/appliance separation are not included the accuracy is :		
							12	0.004	0.011
Discussion	The hand was tracked properly in both cases. There was no any position jumps when holding the device.			2 set of tests were made for the hand tracking to make sure that there is no influence of the frame rate. The standard deviation is unexpectedly high for the second set of tests. Speed tracking is accurate for tracking the hand of the appliance.			Due to the errors in tracking hand and jumps between the hand and appliance position the speed magnitude error is very high. The error is low if speed is estimated only for the forward motion X axis velocity		

The accuracy of speed and position tracking is very dependent on the accuracy of the hand detection algorithms. All the tests were made when the hand was detected properly. As well as that the accuracy can be influenced by the change in the software frame rate. The frame rate of the Kinect software is sensitive to the lightning conditions and computer performance. During the tests the frame rate was stable close to maximum available 30 fps. Only during the first set of tests frame rate was less stable, however it didn't influence the accuracy of the results, this was discussed in the previous part of the chapter.

The error of the hand tracking when holding the hairstyling appliance was expected to be high, because Kinect body tracking algorithms is based on separating body from the environment and other object mainly by distance. Therefore the appliance can be estimated as continuity of the hand. There is a possible solution to the problem. Application of the colour tracking algorithm can allow to separate hand from the appliance, as well as that more advanced filters than a simple low-pass could be applied to minimize the influence of high frequency position jumps. Colour tracking algorithms for separation of the hand from the device is implemented however was not used in the testing due to high influence on the frame rate. One of the project recommendations is to implement the colour tracking algorithms with multithreading that would have a minimum influence on the frame rate.

The first set of tests when holding the appliance showed an accurate hand tracking, however the second group of tests at the speed set to 0.05 [m/s] showed a lot of position change noise due to jumps between the hand and the appliance that resulted in significantly higher speed magnitude error. The velocity over X axis only for forward motion shows a low speed error, based on this it can be concluded that if the hand and appliance will be successfully separated the error of speed tracking will be minimum.

5.4 Microsoft Kinect combined with inertial tracking. Research Results Conclusions

The final program integrates Microsoft Kinect and the BNO055 sensors. Based on colour, depth and skeleton data streams from Kinect the position of the hand is obtained with a frequency of 30 fps. The joint and face tracking algorithms from the Kinect API are used in order to locate the hand relatively to the head of the user. The speed of the hand is obtained from Kinect Skeleton data stream that outputs 3d position of the joint. Colour tracking is less effective in speed tracking due to lack of depth information. The algorithms for separation of hand and appliance by colour is implemented, however not tested due to significant influence on the frame rate during the testing. The orientation of the appliance is sensed with the BNO055 that can be sampled with the frequency up to 100Hz.

The table 5.8 summarises the functionality and accuracies of motion parameters tracking with inertial and Kinect tracking separately and combined. The accuracies of speed, orientation and position tracking for inertial and Kinect tracking are obtained from the tests presented in the chapter.

Based on the presented tests in the chapter it can be concluded that inertial tracking can provide a very accurate and stable orientation tracking with the error lower than 0.06 degrees. At the same time both theoretical estimations and practical tests showed that the error of the speed and position tracking is very high and is not feasible to be used in the given application. Calculations and test with inertial tracking are important because they allow to understand what accuracy of position and speed tracking can be expected with the chosen sensors.

The tests with Kinect position and speed hand tracking showed that the error is small enough and absolutely can be useful for the hair-styling application. There is still a challenge to improve the accuracy of the hand tracking when holding the appliance. Implementation of the algorithm for separation of the hand and the appliance by colour that will not influence the frame rate is the first recommendation for the project. The test results showed that when the errors due to hand with appliance separation are ignored the accuracy of tracking is high. (Test results are shown in tables 5.7 and 5.8).

Table 5.8 that shows the summary of motion tracking of motion tracking with IMU and Kinect is attached in the appendix part A.

CHAPTER 6 – CONCLUSIONS

The presented results of the project allowed to answer the formulated research questions.

Sub-question 1:

What motion tracking techniques are the most suitable for tracking motion characteristics of Philips hair-styler?

As a result of the research the comparison of different motion tracking techniques was made and the inertial-vision tracking systems was chosen as a final solution. The detailed answer on the first sub-question is presented in the chapters 2 and 3.

Sub-question 2:

To which extend inertial sensing method with application of accelerometers, gyroscopes and IMU sensors and chosen vision tracking method can be applied for motion tracking of the Philips hair-styler?

Based on the research, calculations and performed tests it is concluded that inertial tracking is a good solution for an orientation tracking, however is not feasible to be used for position and speed tracking of the hair-care appliances. Estimations were presented that showed the relation between IMU accuracy and position tracking drift, that can allow to conclude on what maximum position tracking accuracy can be expected from any chosen sensor.

While IMU is chosen to be the solution for orientation tracking, application of Microsoft Kinect depth camera is chosen to be the main solution for position and speed tracking of the appliance. Microsoft Kinect joint tracking is used in the application.

Sub-question 3:

What is the accuracy of the orientation, position and speed tracking of the developed IMU - Kinect system?

IMU orientation drift was tested to be lower than 0.06 [degrees/minute].

The errors for tracking hand and hand holding the device with Microsoft Kinect are presented in tables 5.7 and 5.8.

The conclusion can be made that the errors of both position and speed tracking with Microsoft Kinect are small enough to be used with the hair-styling application. However tracking of hand holding the appliance is not stable enough at this stage of the project. The speed tracking error is very dependent on the accurate hand detection. The tests for tracking hand holding a hair-styler with the speed of movement set to 0.05 showed that speed error is completely out of tracking range when the hand is not properly detected separately from the appliance. At the same time results showed that if the hand would be correctly tracked and there would be no position jumps between hand and the appliance, the speed accuracy would be high with an error of 0.004 [m/s] and standard deviation of 0.011 [m/s]. The conclusion can be made that a solution for separating hand and appliance must be found to improve the accuracy of speed tracking. Currently separation by colour is applied, however it is not presented and tested due to the high influence on the frame rate.

As a result of the project the application for hair-styling quantification was developed that can measure and log speed of the hair-styler, orientation and position of the appliance relative to the orientation and position of the user's head. When the application is improved it can bring a lot of value for quantifying the hair-styling process at the product research lab. It should be noticed that currently, hair-styling user tests are constantly performed at the product research centre, however there is no any system for measuring user behaviour.

CHAPTER 7 - RECOMMENDATIONS

There are a number of recommendations that can be taken into an account at the next stages of the project.

Recommendations:

1. Implement multithreading for colour tracking that will reduce the processing consumption and will allow successful application of developed colour tracking algorithms that separates hand and appliance.
2. The frame rate of the developed software with Microsoft Kinect is relatively stable, with the fps close to 30 fps, however the research can be made in order to make it more stable, not taking into an account frame rate variation due to light changes or computer processing power.
3. Study implementation of computer vision algorithms that would allow to perform accurate hand and face position and orientation tracking from the web-camera without application of depth cameras or
4. Research on computer vision algorithms that can add additional functionality to the program such as tracking the length or shape of the hair, obtaining skin, hair colour. During the project simple trial with contour tracking were performed.
5. Finalize the system for the product research centre that can be used to quantify the motion patterns during consumer tests.
6. Keep track of the latest releases of inertial sensors, and depth cameras. Currently depth cameras are being rapidly integrated into laptops and in the very near future can be integrated into smartphones that can allow development of various hair-styling applications with tools that are widely used by consumers.

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APPENDIX

Part A

Table 2.2.5 Summary of motion tracking techniques

Summary of motion tracking techniques					
Tracking Technique	Description	Advantages	Limitations	Conclusions	Visibility
Optical	Technique that is based on measurement of reflected or emitted light. Simple resistive photo-sensors can be used or digital image-forming sensors that are the main components of camera systems.	• Accurate position tracking if with and active transmitter/receiver configuration • Relatively low-cost of implementation, camera from the user's device (smartphone, tablet) can potentially be used. • Can track both object and a head orientation/position at the same time	• Line of sight requirement for position detection, user need to be in front of the camera. • In an active emitter - receiver configuration light emitters must be placed on the user. • Ambient lighting can have an influence on the accuracy of the system if infrared sensing is not used, • Might require a lot of processing power on the external camera device if there are no emitters, markers on the tracked object. • The system speed is lower comparing to inertial or magnetic tracking	Optical system can be a good solution. The placement of emitters on the device is not an option, because hair-styler can be in a very different orientation relatively to the optical sensor that will require a lot of emitters. Camera with application of computer vision algorithms can be used for position tracking of an appliance. Can't pr Depth cameras can be used for position tracking in 3 axis.	Possible to implement, can provide a solution that will feet the main requirement of the system.
Inertial	Combination of accelerometer, gyroscope and magnetometer for motion tracking. Sensor fusion algorithms are used to combine the data from the sensor that would provide and accurate orientation sensing. When orientation is known, gravity vector from the accelerometer can be subtracted and linear acceleration can be determined.	• No line-of-sight requirements • Angular rate measurement with very low noise due to gyroscope application • No emitters/receivers system • Very low latency, very high sampling rates • No sensitivity to interfere with ambient noise or electromagnetic fields • Portable • Relatively low-cost	• Doesn't allow accurate enough position tracking • For tracking appliance orientation relative to the users head another sensor needs to be placed on the head of the user	Inertial tracking is a great technique for orientation tracking. However position tracking in the given application is very challenging.	Orientation tracking can be integrated in the system. Accurate position tracking is not feasible to implement.

<i>Magnetic</i>	There are 2 main configurations of the system: • Active electromagnetic system with an AC/DC generator and receiver coils for position and orientation sensing • Passive magnetic system with magnetometers sensing magnetic field of the earth or permanent magnet.	• No line of sight requirements • Accurate orientation and position tracking • Can track both absolute and relative to the user's head orientation and position.	• Position tracking accuracy can be influenced by the environmental magnetic interference • Receiver sensors need to be placed on the head of the user. • Price of the system can be relatively high • Electromagnetic systems are relatively not portable.	Electromagnetic system can be an effective solution for Philips hair-styler. Adaptive calibration algorithms could be investigated to improve the problem of magnetic interference.	Magnetic and electromagnetic systems are not very feasible to implement. Electromagnetic systems have a high price and relatively complex to implement.
<i>Acoustic</i>	Acoustic systems use the transmission and sensing of sound waves. Determining Time Of Flight of the signal between transmitter and receiver is the main principle for position tracking	• Low-cost, relative simplicity of implementation • Possible high accuracy of tracking	• Line of sight requirement. • Low speed of the system • Due to device rotation the signal transmission or receiving would need to be omnidirectional • For the given application there will be very high interference that would not allow accurate tracking. • Requirement of minimum 3 receivers for position tracking	The system is not suitable for accurate hair-styler localization around the user's head.	Paper of hand tracking relative to head with ultrasonic system[22]
<i>Radio and microwave sensing</i>	Radio wave positioning systems consist of a transmitter and a number of receivers. The position of the transmitter can be determined by measuring Time of Arrival, Time difference of arrival or Angle of Arrival of the transmitted wave.	• No clear line of sight requirement • Relative low cost • Requires relatively low processing power.	• Does not allow orientation tracking • Require minimum 4 or 3 receivers places • Low accuracy in the range of meter. Only a number of research papers showed accuracy of 4-10 cm	The system is not very suitable due to low accuracy and a high number of receivers. Low cost and possibility of accuracy improvement are good points	Is not feasible for implementation due to low accuracy and big number of nodes

Figure 4.1 IMU testing design.

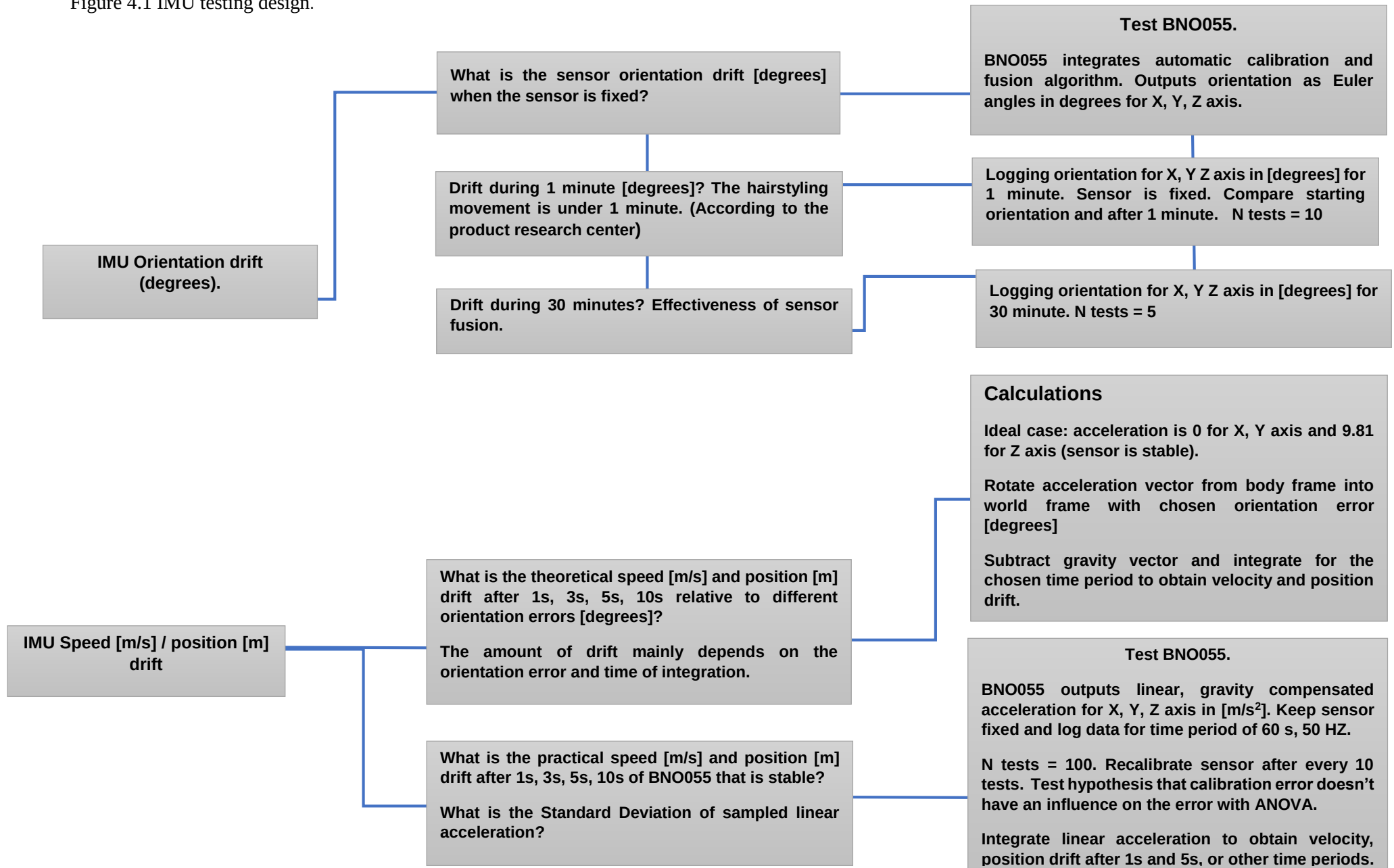


Figure 4.2 IMU Kinect speed and position accuracy testing design

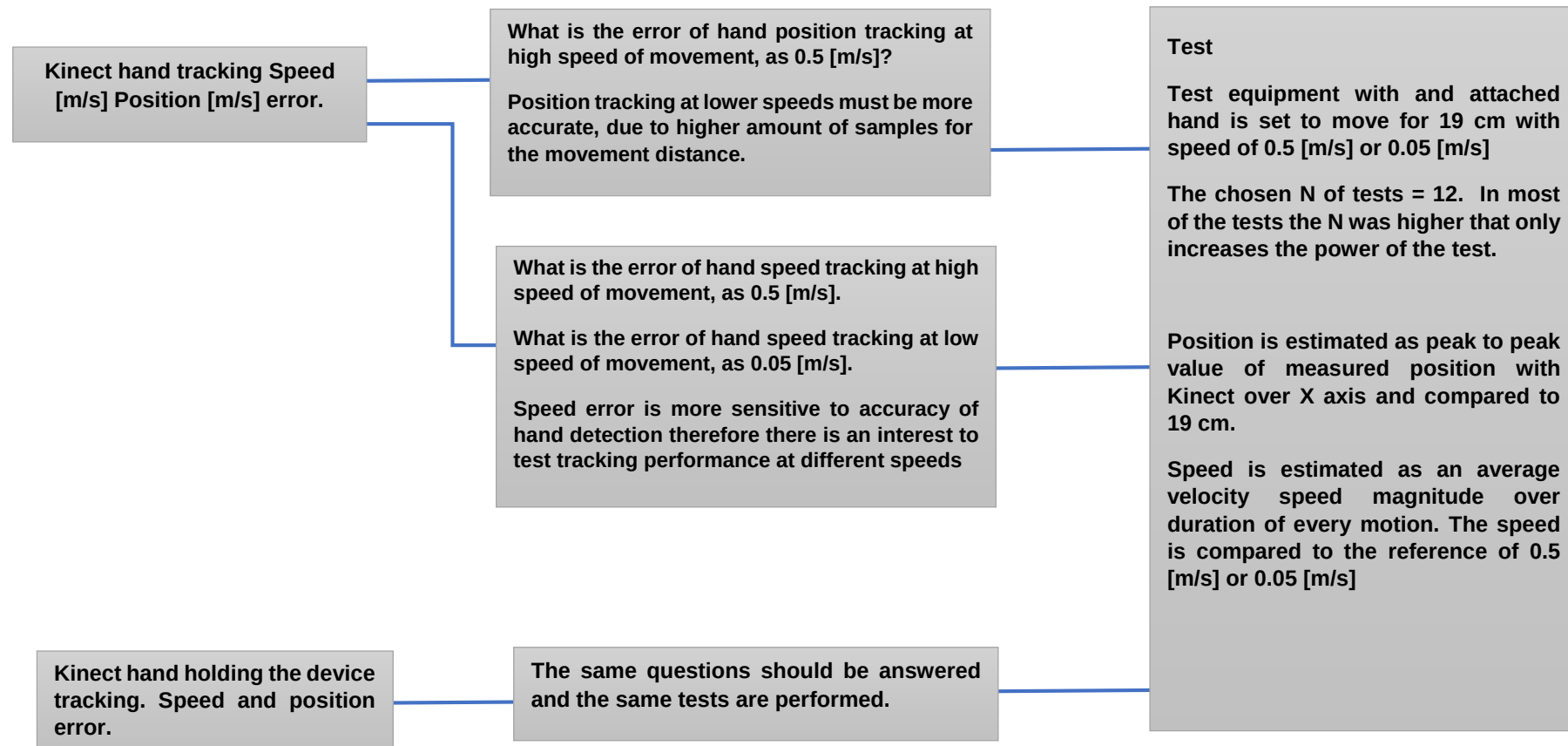


Table 4.1 Hardware Sensor Fusion modules comparison

IMU name	BNO055 SD +/-1.1	MAX21100 SD+/- 2.2 Stable TOP	EM7180 SD +/-4 Stable/Depends on input	MPU6050	MPU9250	LSM9DS0
Desctiption	Complete 9DoF Sensor fusion package	Motion Merging Engine (MME)	Motion Sensor HUB	DMP(Digital Motion Processor)	MPU6050 integrated magnetometer and 6DOF DMP	
Accelerometer	BMX055	MAX				
Gyroscope	BMI055	MAX				
Magnetometer	BMM150	LIS3MDL			AK8963C	LIS3MDL
Pressure	Yes	No	Yes	no	no	no
Accelerometer Hz	2kHz	2kHz	2kHz			
Gyroscope Hz	8kHz	8kHz	8kHz			
Magnetometer Hz						
Sensor Fusion and Features	9 DoF fusion. Extended Kalman, low and high pass, autocalibratiron, temp. compens.	9 DoF	9DoF extended Kalman filter, autocalibration, low-and high-pass filtering, magnetic anomaly detection	6DoF fusion	6DoF fusion	6DoF fusion
Interface	I2C/UART	I ² C/SPI	I2C	I2C	I2C	I2C/SPI
Price \$	5.50\$	7.50\$	7\$	\$2	3\$	3\$
Pros	Complete sensor fusion. Linear acceleration output Automatic calibration	1.7V; Great sensor fusion	Can combine various sensors	Easy to interface	Easy to interface	
Cons						
Links	Link1	Link1	Link1			Link1
Other boards	ITG-3200, FreeIMU, MultiWii					

Table 5.8 Summary of motion tracking with IMU, Kinect and combined system.

	IMU (BNO055)	Microsoft Kinect	Fusion
Orientation	< 0.06 degrees	From literature 0.8 -2 degrees [33]	< 0.06 degrees
Speed error [m/s] @1 s	0.0864 [m/s] STDEV 0.0307 [m/s]	Hand tracking error without an appliance, based on the tests • 0.075 [m/s] STDEV 0.011 [m/s] @at the reference speed of [0.5 m/s] • 0.037 [m/s] STDEV 0.126 [m/s] @at the reference speed of [0.05 m/s] Hand tracking error with an appliance (When hand is tracked correctly) : • 0.145 [m/s] STDEV 0.061 @at the reference speed of [0.5 m/s] • 0.004 [m/s] STDEV 0.011 @at the reference speed of [0.05 m/s] if the error of hand detection is completely ignored • The tests showed that if the hand is not separated accurately from the appliance, the speed magnitude error is very high	
Speed error [m/s] @5 s	0.452 [m/s] 0.215 [m/s]		
Position error [m] @1 s	0.0432 m STDEV 0.0165 m	Hand holding an appliance tracking error: 0.022 m STDEV 0.011 m Hand without an appliance: 0.013 m STDEV 0.012 m	
Position error [m] @ 5 s	1.133 m STDEV 0,523 m		
Other		Possible additional functionality Face position / Face Orientation /Face parameters/Heart rate/skin and hair color/ other	
Problems	Very low speed and position accuracy	Orientation and Position tracking is sensitive to occlusion	Position tracking is based on Kinect, therefore position is sensitive to occlusion

