DiverNet - a Network of Inertial Sensors for Real Time Diver Visualization

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***Abstract*—This paper describes the DiverNet system that allows real time reconstruction of diver's posture and its visualization using a virtual 3D model. DiverNet is a network consisting of 17 inertial sensors mounted on diver's body, enabling calculation of orientation of each body part. Based on the obtained data, diver posture can be visualized. In addition to that, DiverNet allows integration of additional sensors for measuring physiological parameters such as breathing rate. This is the first time such technology is used in the underwater. Obtained data will be used to increase diver safety by monitoring the diver in real time, as well as developing tools for understanding diver behaviour and automatically recognizing possible signs of trouble. The paper focuses on technical description of the developed system, as well as the software used for data analysis and visualization.**

I. Introduction

SCUBA diving is an extremely dangerous activity for a number of reasons. Firstly, divers depend on technology for life support, and even a minor malfunction can have catastrophical results. Secondly, the mere nature of long term exposure to high pressure at high depths can have significant negative effects on diver health, such as decompression sickness or nitrogen narcosis. While decompression sickness can be cured more or less successfully on dry land, nitrogen narcosis occurs underwater and can result in unpredictable diver behaviour that may lead to fatal actions such as releasing the breathing regulator, exceeding the dive depth or disregarding the diving plan in general.

These problems are usually dealt with by pairing divers and thus significantly reducing the chance of disaster. However, an inexperienced dive buddy may not even notice a dangerous state such as nitrogen narcosis. The best way to avoid diving catastrophes is by ensuring proper and timely reaction through monitoring divers from the surface, as well as from underwater.

Monitoring for the purpose of determining a person's posture can be done either by using remote or local sensing techniques. Remote sensing techniques on dry land include visual sensing aided by depth cameras, such as Kinect. The newly developed algorithms provide fascinating computational efficiency and robustness in real-time human pose recognition and individual body parts from single depth images. Another remote sensing approach includes using multiple cameras to obtain stereo images that facilitate 3D pose estimation and can increase robustness [1]. Local sensing using commercially available low cost inertial sensors for pose estimation and reconstruction has proven effective and was utilized in a variety of sports [2][3][4], medicine [5], as well as in film industry. In the sense of pose estimation, inertial sensors are usually used to determine orientation and movement of individual body parts with respect to Earth-fixed frame, in an area of unlimited size with no supporting infrastructure such as positioning of cameras.

Traditional remote sensing systems are severely hampered in aquatic environments, due to problems imposed by water. Visual sensing suffers from low range due to water turbidity, and depth cameras are not applicable underwater due to high attenuation of infrared spectrum. These are the main reasons why local sensing based on inertial measurements can give the most reliable posture reconstruction. Some local sensing applications in water have been reported but they do not include full submergence of sensors: in [6], [7] accelerometers were used to measure acceleration profiles and activity of swimmers; in [8], the system for measuring temporal kinematics of a freestyle armstroke was tested on a swimming bench.

This paper presents DiverNet, an underwater wearable network of inertial sensors for diver pose reconstruction. Based on available literature and authors' knowledge, this is the first time such a network has been developed and tested on divers in real underwater environment. In addition to the hardware development of DiverNet, this paper also focuses on the visualization software that, for the first time, allows real time visualization of diver movements in the form of a virtual avatar displayed on the screen at the ground station. We state with great confidence that DiverNet can change the way diver monitoring is performed and can significantly reduce underwater accidents by anticipating suspicious diver behaviour through posture analysis. In addition to that, DiverNet can be augmented with a number of physiological measurement

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devices, such as breathing or heart rate monitor, that can provide valuable information to the diving supervisor at the surface. This paper also presents integration of a commercially available breathing belt in the DiverNet.

II. Hardware

This section details the electrical hardware and mechanical construction of the DiverNet system. We start by presenting the design of the central DiverNet 'hub' before giving further information about the inertial and physiological sensor networks.

A. DiverNet hub

DiverNet hub is the central processing and acquisition unit of the sensor system, coordinating the sampling of up to 20 inertial sensor nodes and the relaying of the acquired data to the surface. The block diagram shown in Fig. 1 details the structure of the proposed system. The central hub utilizes a system on chip (SoC) Atmel ARM processor to sample and process each of the sensor readings. The processor samples a network of hardwired inertial sensors and communicates the raw readings to the surface through a tethered connection. The data can then be processed and visualized in real-time at the surface. A range of alternative communication links are also integrated into the system, enabling data to be streamed to other external devices e.g. a tablet, watch or acoustic modem.

1) Sensor communication interface: Communication between the DiverNet hub and the inertial sensor network is performed by an Inter-Integrated Circuit (I^2C) bus. The I^2C protocol allows a network of multiple sensor nodes to be connected utilizing shared data and communication lines. In this scenario, to ensure all channels are sampled simultaneously and within the given sample period (20 ms), a parallel data bus is used, supplying each inertial sensor node with its own independent I^2C data line. Although an I^2C network is typically configured as a serial topology, the overhead of the I^2C protocol significantly limits the number of nodes that can be sampled sequentially within the given time period. This effect is further exaggerated if a lower clock frequency is used to ensure reliable operation over cable lengths of greater than 1m, and if multiplexers are required to avoid addressing conflicts on a shared data line.

The developed system utilizes a global clock and 20 parallel data channels. Each of the I^2C data lines is connected to a digital IO pin, with the port being manually 'bit-banged' by the processor during transmission and reception. By connecting the data lines to sequential IO pins the port can be toggled using single instructions, allowing read and write operations to be performed within the tight time constraints of the I^2C protocol. To minimize the fanout effect, observed on the global I^2C clock line, a buffer is integrated into the system. The 1:4 clock buffer enables the I^2C clock to be distributed to the separate sub-networks, minimizing the fanout effect of driving all 20 sensors and ensuring minimal clock skew. By utilizing a global clock to control all nodes the system inherently insures readings are made from all nodes simultaneously.

Although the current design utilizes a hardwired connection to each node, future work will focus on the development of a wireless communication scheme to network the inertial sensors to the central hub.

2) Communication link: Communication between the DiverNet hub and the surface is facilitated by a tethered RS-485 connection. The RS-485 link utilizes a differential pair to allow data to be transmitted at ranges of upto 1.5km. At shorter ranges, typical to this application (e.g. $\approx$100m), the link can support throughputs in excess of 1MBps. The raw binary data is transmitted to the surface in a bespoke packet structure. Each packet has a fixed packet length of 366 bytes, consisting of: 4 header bytes (representing the ASCII characters 'D1Ve'); 2 bytes for each X,Y and Z reading of each sensor (accelerometer, magnetometer and gyroscope) - e.g. 18 bytes per sensor node; and a 2 bit cyclic redundancy check (CRC-16) checksum.

In the future, the processing performed at the surface will be migrated into the DiverNet hub, with compressed information being relayed to the surface rather than high bandwidth raw data. The tethered connection will then be replaced by an acoustic communication link, removing the restriction on the divers manoeuvrability caused by the tether.

3) Mechanical Housing: The DiverNet hub is enclosed in a housing machined from 5083 grade aluminium, utilizing SubConn micro connectors to connect with the inertial sensor arms, breathing belt and surface tether. The approximate housing dimensions are 150mm x 85mm x 50mm and is designed to fit on the rear of the divers air tank. A photo of the housing construction with mounted processing PCB is shown in Fig. 2.

Fig. 2. DiverNet hub mechanical construction: Aluminium 5083 housing with main processing PCB and micro SubConn interface connectors

B. Inertial sensor system

1) Sensor positioning: The proposed sensor placements are shown in Fig. 3. These locations are defined as: 1. Apex of the head; 2. Sternal notch; 3. Lower back; 4. Shoulder blades; 5. Lateral surface of the upper arms; 6. Lateral surface of the

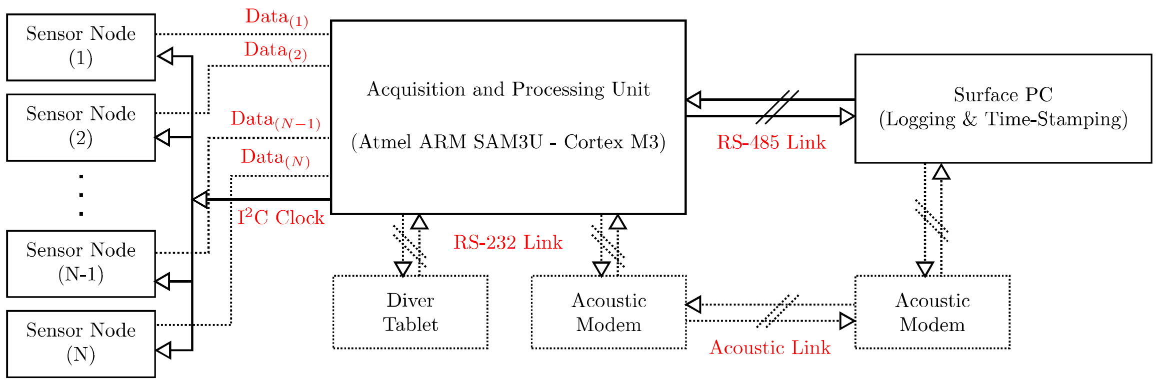

Fig. 1. Block Diagram: DiverNet System

lower arms; 7. Lateral surface of the thighs; 8. Anterior surface of the shanks; 9. Back of the feet; 10. Back of the hands.

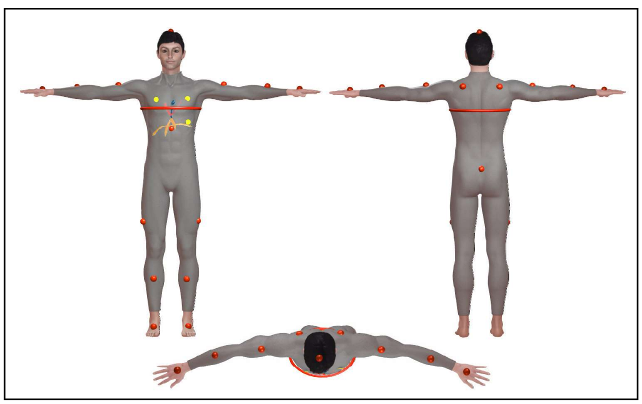

Fig. 3. DiverNet sensor positions: Red dots - Inertial sensor node positions (x20); Red band - Breathing belt position

Based on the symmetry of the sensor positions the network is split into 4 sub-nets, each referred to as a sensor 'arm' and covering a quadrant of the bodies position, e.g. upper left, bottom left, upper right and lower right. A total of 20 nodes are included in the network, with each sub-network consisting of 5 sensor nodes. This allows 3 spare nodes to be included for additional redundancy in case one of the main nodes fails, due to water ingress or mechanical fatigue.

2) Sensor Node Specification: Each of the 17 sensor nodes house a Pololu MinIMU-9 Inertial Measurement Unit (IMU). The module consisted of three 3-axis sensors, enabling the rotation, acceleration and magnetic field to be measured at each position. The nine Degrees of Freedom (9DOF) independently measured enables the system to accurately calculate the sensor's absolute orientation as detailed later in this paper. The three sensors were combined onto a 20mm x 12mm PCB, weighing < 1g, making them suitable for mounting at multiple positions on the diver. All of the sensors operate as a slave device, sharing a common I^2C data and clock line. The data rate of the I^2C bus is manually clocked by the master DiverNet hub, allowing the clock frequency to be varied as required to meet the sampling specification.

The specification of the accelerometer, magnetometer and gyroscope combined in this module are detailed below:

- **Accelerometer:** 3-axis accelerometer, 16-bit resolution (per axis), variable sensitivity range: $\pm 2, \pm 4, \pm 6, \pm 8$ or ± 16g (max).
- **Magnetometer:** 3-axis magnetometer, 16-bit resolution (per axis), variable sensitivity range: $\pm 0.2, \pm 0.4, \pm 0.8$ or ± 1.2mT (max).
- **Gyroscope:** 3-axis gyroscope, 16-bit resolution (per axis), variable sensitivity range: $\pm 245, \pm 500$ or $\pm 2000°/s$ (max) .

In the initial design all sensors are selected to operate using the maximum sensitivity range, e.g. accelerometer = ± 16g, magnetometer = ± 1.2mT, gyroscope = $\pm 2000°/s$. To ensure the most up to date readings are acquired, each module is configured to update the output buffer at the highest update-rate possible ($\gg$ 50 Hz). Each buffer is configured to only hold a single reading, with older samples being over-written when new data is available.

3) Sensor Housing: To ensure the sensor package is successfully protected a bespoke sensor housing has been developed. The sensor housing protects the electronics from water ingress and any physical contact the diver might make with any subsea structures. The dimensions and ergonomics of the package ensure that the unit can be easily mounted at range of different locations on the diver. The unit is compact and shaped with rounded edges, such that: it does not become snagged on other pieces of equipment; avoids any discomfort to the diver; and does not constrain the divers motion while swimming.

The shape of the housing is inspired by a basic digital watch, with two strap loops protruding from the side of the case. It allows easy attachment and removal with straps, avoiding the need for permanent fixings to be mounted on the divers suit. To reduce development time the housing was 3D printed. Although the printed housing is water permeable the enclosed circuitry has been designed to 'float' inside the centre of the housing on two mounting pillars. Once the PCB is mounted and electrically connected the inside of the housing is filled with a polyurethane (PU) potting compound. The lack of air pockets ensure the board is waterproofed and capable of operating at suitable depths for the proposed testing.

Fig. 4 demonstrates the construction and connection of two sensor nodes as part of the daisy-chain network. The sensor housing on the left is shown mounted in a construction jig, ensuring the node remains stable during the potting process. Once the construction process is complete and the node is fully potted in polyurethane (PU) the sensor housing is removed from the jig.

Fig. 4. DiverNet sensor node construction with daisy-chain wiring topology

4) Network Construction: Each limb consists of 5 inertial sensor nodes, four connected in a 'daisy-chain' serial topology and the fifth as a spur from the first node. This topology matches the required placement detailed previously, with the four series elements stretching along the extremities of the divers limbs (e.g. along arms and legs) and the fifth element utilized for more centralized readings (torso, lower back and head). The interconnects between nodes utilize a shielded 8-core cable, supplying: ground; supply voltage; global I^2C clock; and 5 independent I^2C data lines.

C. Physiological Sensor Interface

In addition to the inertial sensors network, the DiverNet has the capability to interface with a range of other physiological sensors. The current system utilizes an internal 12-bit ADC, combined with a pre-amplification and filtering interface board to sample a piezeo-electric breathing belt. Additional 10-bit, 12-bit and digital IO ports are also available for interfacing with other sensors.

Within this project a breathing belt is utilized to monitor the divers respiration in various dive conditions. A commercially available breathing belt, developed by UFI (Pneumotrace 2), is utilized to sample the divers breathing. The breathing belt utilizes a piezo-electric transducer, flexed by a stretched rubber band, to passively generate a small voltage related to a change in the divers thoracic circumference. Into a 1MΩ load the belt is designed to generate an output of 20-50mV. In order to effectively sample the output with the 12-bit ADC (input range 0-3.3V) a basic signal conditioning circuit is constructed, consisting of: an active second order low pass filter, in combination with a passive high pass RC level shifting circuit. The circuit supplies a gain of $\approx$47dB, with a highpass cutoff of $\approx$0.015Hz and a lowpass cutoff of $\approx$15.4Hz.

A sample of data collected from the breathing belt, using the DiverNet system, is presented in Fig. 5. Utilizing the discussed signal conditioning, adequate gain and filtering is supplied in order to analyse the Divers breathing rate.

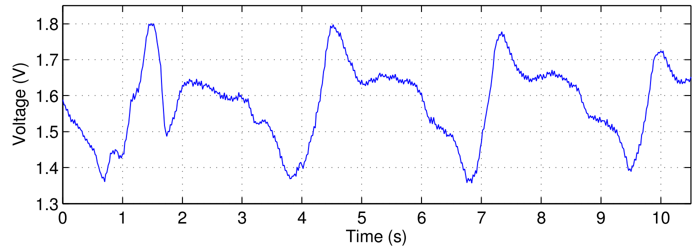

Fig. 5. Breathing belt (UFI model 1132) output from DiverNet system

III. SOFTWARE

The entire software for DiverNet was developed using Robot Operating System (ROS) [9]. ROS is one of the most popular software frameworks in the field of robotics. It provides great flexibility with its concept of nodes and makes it easy to create software that is modular and easy to integrate.

A. Architecture

The software architecture was developed to give as much flexibility for the use of DiverNet in the future. Block diagram representing the current state is shown in Fig. 6. Processing is split in multiple nodes, allowing easy substitution (or complete bypassing) of a certain stage. For example, the processing node which performs the filtering can be replaced with another one, giving the option of testing several different filters and plugging them in as desired. Also, the block diagram shows final visualization in ROS RViz visualization package, but later we will show that the output data can be used for other types of visualization format as well.

B. Data processing

1) Reading raw data: The first step in the processing chain is to get the data via tethered connection from the DiverNet hub. A ROS node is used to read the accelerometer, gyroscope and magnetometer data for each of the sensors. It calculates the CRC checksum to detect possible errors in transmission. If the check passes, the values are normalized and publish for next node to process.

2) Calculating and filtering individual sensor orientation: The raw sensor data acquired from the IMU units is then used to calculate the orientation for each of the individual sensors. This is done in two steps:

- Getting raw orientation estimate based on magnetometer data and gravity distribution along the accelerometer axes.
- Fusing data from gyroscope with previously calculated raw orientation in a filter, resulting in a more precise estimate of orientation.

A number of research papers and algorithms have been published on the topic of sensor fusion for orientation estimation.

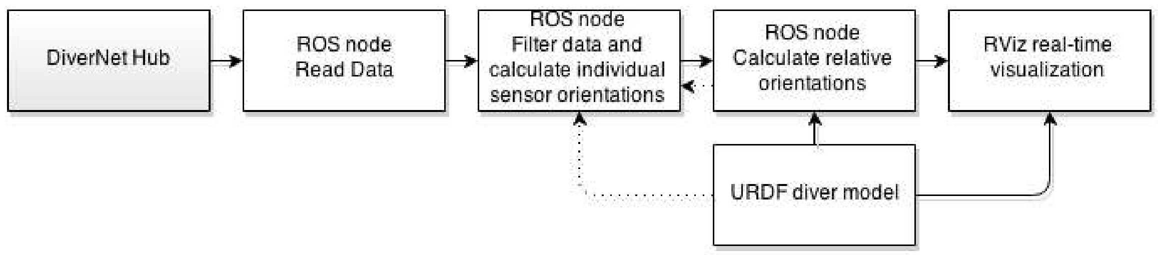

Fig. 6. Block Diagram: Software Architecture

Most of them are based on Extended Kalman filtering [10][11]. Other popular approaches are based on complementary filtering, with the so called Madgwick-Mahony filters emerging as a great alternative to computationally more expensive Kalman filters. [12][13]
In our initial version a simple Euler-angle based complementary filter with adaptive coefficients is used for this task. Angles roll, pitch and yaw are calculated for each of the sensors as:

$$\hat{\varphi}_r[n] = a_r[n] * (\hat{\varphi}_r[n-1] + \omega_r[n] * dT) + (1 - a_r[n]) * \varphi_r[n],$$

where subscript r denotes one of the Euler angles, φ_r is the Euler angle calculated from accelerometer and magnetometer data, $\hat{\varphi}_r$ is filtered angle, ω_r is the component of angular velocity around the relative body axis matching the Euler angle, dT is sampling time and a_r is the adaptive filter coefficient dependent on the difference between filtered and raw angle values. By having the adaptive filter coefficient we can make sure that the possible drift of the gyroscope data will be compensated.

3) Combining individual orientations for the whole model: Finally, the third step is to join the previously calculated individual orientations for each body part into a whole body model. For this purpose ROS tf2 package is used. It provides tools for keeping track of multiple coordinate frames over time. By providing it with a tree representing our model (where each pair of body parts connected by joints are parent and child), tf2 can transform individual (absolute) orientations into orientations relative to the parent. This type of data can be used in a variety of visualization formats.

C. Visualization

In this section the visualization process will be described.

1) Diver model and visualization in RViz: The main model used for real-time visualization was developed in Unified Robot Description Format (URDF). It creates a tree-like structure which describes relationships between body parts, body part sizes and joint types. Besides for visualization, the model is also used in other processing stages. As shown by dotted lines in Fig. 6 it is required for relative orientation calculation stage, and can also be used to improve the filtering process. Currently only some basic limitations for the degrees of freedom of the joints are used in that stage, but a more complex filtering model which exploits model structure and adjusts the model by estimating body parts sizes is planned for future work.
For the visualization itself, simple 3D objects were used at first to represent body parts (spheres, boxes and cylinders). They were later replaced with realistic diver mesh models developed at Jacobs University Bremen.
The main tool used for visualization is RViz, a visualization tool for ROS. By providing RViz with the robot description (model described above) and relative body parts orientations it can display the diver model in real time.
In Fig. 7 initial and final diver models are shown, rendered in RViz.

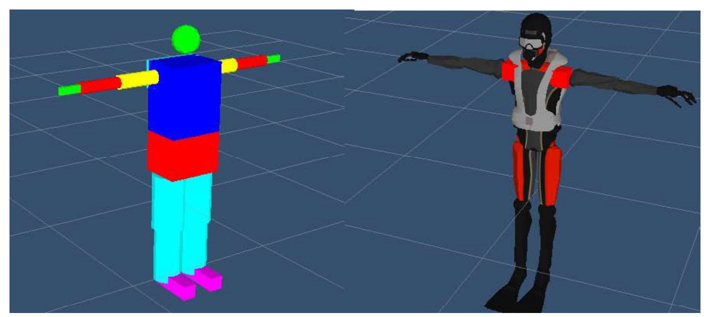

Fig. 7. RViz visualization of the initial and final diver model.

2) Visualization with BioVision Hierarchy: Besides URDF model and RViz visualization, a BioVision Hierarchy (BVH) model was developed for use in many commercial visualization programs. BVH uses a model very similar to the URDF one and shares the relative body part orientation data, making it easy to produce them both. Advantages of using BVH data is that the user does not need to have ROS and RViz installed on their computer, but it is not suitable for live visualization.

IV. Field Trials and Results

Two field tests with DiverNet have been performed so far. The first one was held in Caska on island of Pag, Croatia, where a group of students conducting archaeological excavations have volunteered to take part in initial trial. A total of six divers took part in trial, performing given tasks. Velcro stripes were used for sensor mounting, taking in average around 25 minutes to mount per diver. This was the first time DiverNet was used in real-life conditions at sea. It performed without problems and a total of approximately 4 hours of data was recorded and will be used in diver behavior study. Fig. 8 shows the diver with mounted DiverNet during the Pag field trial.

Fig. 8. Diver with DiverNet during Pag trial

Second trial was performed on Y-40 pool in Padua, Italy. A total of 16 divers (amateurs and members of Divers Alert Network Europe) have participated in tests that were designed to cause exertion. Mounting system was improved with rubber elastic bands, taking around 10 minutes per diver to mount. DiverNet performed again without problems and several more hours of data was recorded. Fig. 9 shows two screenshots of the virtual diver model during Padua experiments. Videos are available at CADDY FP7 project Youtube page: https://www.youtube.com/user/caddyproject.

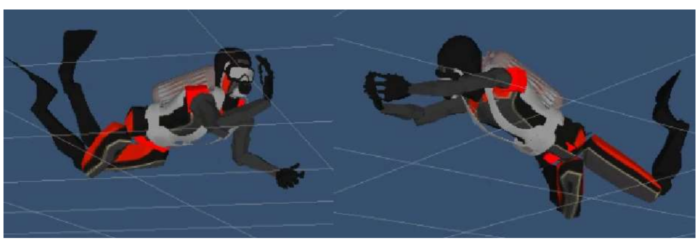

Fig. 9. Screenshots of RViz visualization from field trial in Padua.

V. Conclusions and future work

In this paper we presented the newly developed DiverNet system for real time diver posture visualization. Although on dry land much cheaper devices (such as cameras and depth cameras) can be used with high precision, specific underwater conditions degrade their performance or make them completely unusable. In such conditions we find that our IMU based system is a great solution. Based on initial experiments conducted with divers in real life conditions we believe that DiverNet will prove extremely useful for keeping track of what the diver is doing in real time and react in case of any sign of trouble. This can already be done by a human monitoring from the surface, but will in the future be enhanced with tools for automated diver behaviour tracking and analysis based on DiverNet data.

Based on these two field trials and experiments from the lab, the following plans were made for the future:

- Improve data processing step by developing a more efficient filter. Attempt to solve the kinematic model for each individual diver by going through an initialization step. Some work on this was done in [14][15][16].
- Test the system's accuracy with camera and depth imaging as reference points.
- Improve mounting system. Although elastic bands were an improvement over velcro stripes, the sensors still can't be strapped tightly enough to keep them completely fixed on their position. Also, occasional strap detachment would cause an individual sensor to fall off and becoming useless until put back in place.

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