A Versatile Networked Sensing System as Add-On System for Augmenting Sports Devices

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Abstract— **In this paper, we present a novel sensing platform for training support in sports. Ubiquitous computing applications have been especially interesting for this area as sensing technologies allow unobtrusive integration and for information acquisition that formerly was not possible. The developed networked sensing system can be attached to any piece of sports equipment that either has an axis of rotation, e.g. a gear box or a belt system. We specifically target at high-priced sports equipment for sports schools and fitness studios. Here, often no integrated measurements systems are available, despite the high price of the robust machines. We present the sensor device, the overall system architecture and the algorithms to convert acceleration into Joule, a unit of great importance to trainees.**

I. INTRODUCTION

During the development process, we could incorporate our experience of designing ubiquitous computing systems in the field of sports [1]–[4]. The focus of this work though does not lie in the design and development process as in our earlier work [5], but on a flexible networked sensing platform for a great variety of sports devices. The sensor system and the algorithms can, with out any change, be used for any existing piece of sports equipment that either has an axis or uses rotation like the synchronous training machine (see Fig. 1) or uses belts or cords to translate motions of training machines.

The advantage compared to existing sensor-augmented systems that usually have sensor system e.g. in a gear box of the sports device is that our system can be used as add-on. This has several advantages: usually manufactures do charge a significant amount of money for the inclusion of sensors in gearboxes due e.g. the complexity of manufacturing and additionally software systems from the same manufacturer have to be obtained. This often results in data conversion problems between these systems and existing training systems that already exist e.g. in a sports school. Easy integration e.g. for automatic training analysis and training plan generation are thus additionally costly, if even possible. Our system allows easy bindings to existing training systems and integration with the additional benefit that our sensor box can be attached outside the training device and also to training devices that are not yet sensor augmented by the original manufacturer.

For a comprising discussion of related work of sensing systems we would like to refer the reader to [6].

II. SYSTEM DESCRIPTION

Fig. 1. The Synchronous Training Machine: the gear box on the axis does not allow for sensor inclusion. No sensor system from the sports equipment manufacturer can be obtained, which is true for many other systems as well. This is just an example of many expensive sports devices that can be augmented by our proposed sensing system.

The system consists of a sensor device for measuring an angle of a lever or belt running over an axis by a two axes acceleration sensor and a middleware for processing the acceleration data and calculating the lever's angle and a graphical user interface for visualisation. The sensor is able to detect static and dynamic acceleration. From rotation and angles our software calculates the energy in Joule the trainee generates by his training.

The requirements, as presented belows, were derived using the same user-centred design process as described in [5]:

- High accuracy, only small variations of sensor data allowed (desirable < 10mG) Problem high frequent noise
- High sampling rate > 50Hz in the middleware, 1260Hz on the sensor device
- Measurement of angles in degrees with an accuracy of 1° at least and a latency of max. 15ms
- High measurement resolution: desirable 1mG
- High stability of the measurement data against environmental changes like e.g. temperature
- Low voltage (5V)
- Low power consumption
- Low costs and easy installation by non-technicians

These challenges can partly be met by a stable power supply that minimizes voltage fluctuations which may influence the data measurement and a high qualitative acceleration sensor with high resolution. Extensive finetuning though is necessary.

A. Sensor Device

a) Synchronous Training Machine: The prototype will be discussed in the application context of the synchronous training machine, though it can be attached to a great variety of training systems as explained before. The Synchronous Training Machine, as depicted in Fig. 1, is a robust and very popular training system despite its price of EUR 2400. The manufacturer does not provide any electronic measurement system for this and other devices. Though, a sensor-augmentation is desireable for both the trainee as well as the sports school for more effective training support. It is surprising that e.g. ergometers can be obtained with much elaborate sensor and system support even for consumers for a couple of hundred Euros but not for a high-priced professional training system. This can partially be attributed to the amount of regulations and associated costs that a electronic device has to comply to, e.g. from a safety point of view, to be allowed for sale.

b) Prototyping: The first prototype used the Particle Computer sensor network platform for rapid prototyping. Special add-on boards with different acceleration sensors have been build to assess the potential of sensor augmentation of several systems and to evaluate the measurement frequencies. This step also already allowed for algorithm development of testing to translate acceleration into Joule, a unit of greater importance to trainees than acceleration or rotation.

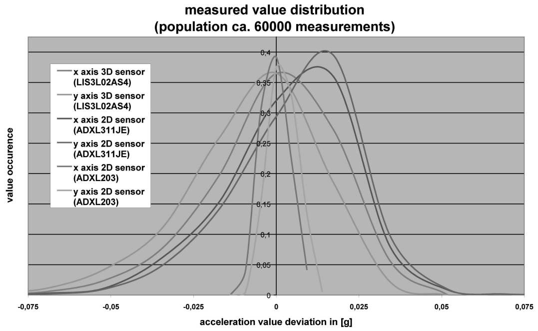

Fig. 2. Acceleration sensor testing and tuning helped to select and improve the measurement range to a maximum. The deviation of the used sensor is minimal.

After the rapid prototyping phase we switched to a simpler design comprising only the PIC microcontroller and no RF chip. This has been especially necessary as the RF communication bandwidth available with the Particle Computer platform would limit the number of potential devices to only a few – a surely undesirable situation in a real sports school where there often are more than 50 devices.

A PIC 18F2550 microcontroller and an ADXL203 acceleration sensor were chosen as basis for the measurement system. This ADXL sensor provides higher resolution, more accurate measurement data and less noise than the formerly used sensors during prototyping. The ADXL's measurement range was fine tuned by selecting appropriate capacitors and additionally the reference voltage for the PIC's analog to digital converter as changed to achieve optimal measurement data. Serial data transmission was added with a serial-to-USB converter from FTDI that has the converter part in the USB B connector.

The price of the overall platform has been minimised so that it is, even in the presented prototype design, very competitive.

c) Design Decisions: We explicitly opted for an installation-based, wired system for the following reasons: An installed system that loads the user's training data after authentication with a RFID card integrates much easier into the existing system, users already have such a card and use it as authentication token when entering the sports school or fitness centre. The card itself is small and cheap and fits into the pockets of a track suit. Carrying a much heavier PDA or another mobile device is much more cumbersome in a scenario where training device changes occur frequent and rapidly. Additionally, chances are high that, a PDA placed on the floor or in a socket of the training device, will be damaged due to falling weights or accidents. The costs of a mobile device also are huge and would have to be paid either directly indirectly via the member fees by the trainee. The data currently is stored on the systems of the sports school. Storing it additionally on a user device could be achieved more easily with a cheap USB stick - if it is desired at all to give the user this data. Binding users to the sports school and not giving him the data may additionally be a desired 'feature'. As the trainers in fitness centres and sports schools regularly meet with the trainees to develop new training plans, there are little arguments for storing this data additionally on a user device as they are used to optimise the plans. Regarding the number of training devices of an average-sized fitness centre and the numbers of users along with the necessary speed constraints discussed above, a wireless solution offers no additional advantage to the user, while adding an additional point of failure. Also, 'pairing' user device and sports device takes time, which would add a significant amount of time per station - some exercises with e.g. 25 repetitions itself take less than a minute to complete while selecting the training device, pairing it, etc. would surely take about 30 seconds.

B. System Architecture

The second prototype of the system as describe in this paper (Fig. 3) only supports one sensor and one graphical user interface client per server. This is an intermediate system design. The server application processes the measurement data from the sensor device. The server then pushes the timestamped acceleration values via TCP to the visualisation component, a Flash GUI, which is developed in Actionscript. Flash allows a fast development of user interfaces which reduces the time for prototyping. This implements a Model-View-Controller model, where the server represents the model and the Flash application the view. So the view does no processing of data, and only shows the results of the server's computation. To exchange the data between the server and the Flash GUI a simple protocol is used. Data structures are transmitted via XML and commands are sent by key words and comma separated attributes.

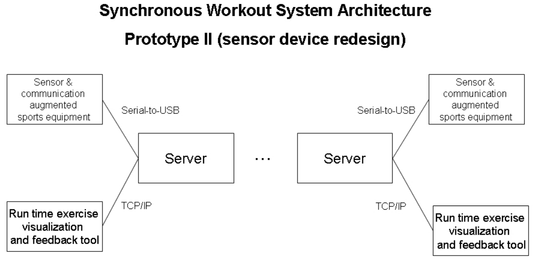

Fig. 3. The architecture of the networked sensing system in the second iteration is shown. The next iteration will allow for multiple sensor and visualisation components per host PC. This further reduces costs.

To avoid inconsistent states of the server application and the Flash GUI both applications implement a state pattern for the communication. The behaviour of e.g. the server's *Connection* object is realized by several states. The *Connection* object is responsible for the protocol and the application flow. Fig. 4 depicts the system design in UML. The states avoid inconsistent program states, even if an implementation error would exists i.e. in the protocol by an key word in an unexpected situation the server wouldn't crash because the server accepts in each state only certain instructions. The program flow is also regulated by the state pattern, i.e. the measurement values of the sensor are only processed in the Training state. Each state also represents a certain screen in the Flash application. Thus it is very easy to add new states to extend the application and new GUI screens.

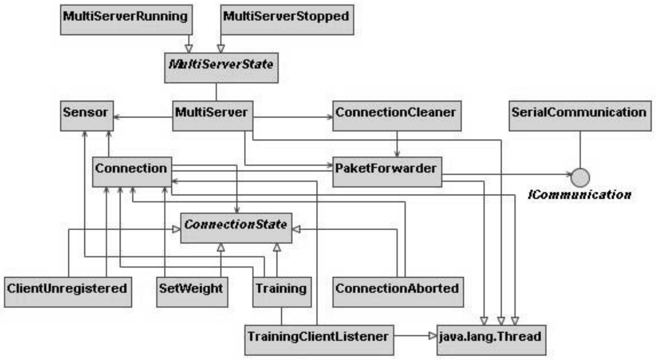

Fig. 4. The architecture was realized using state patterns. This assures that even in case of system failure or transmission errors the state of the application is always defined.

d) GUI: The fist prototype used a database the administrate, the athletes data, like the workout plan which includes training milestones, progression rates of weight and work and a repository for the workout data to analyse the workout progression by a trainer. In the database are the processed measurement data of a workout session saved to analyse them to gain information of the training's efficiency. Also a long term observation of the athlete's condition progress is possible. This will increase the long term motivation of the athletes. The second prototype abandons on the database connection to simplify and speed up the application development to collect user experience with the graphical user interface and the provided visual feedback. The next prototype will include a further development of the database connection and functionality.

The user interface, as depicted in Fig. 5, gives visual feedback during exercises. It allows monitoring of the motion range and the current position of the legs by tracking the machine's working lever. A needle, as known from speed indicators, represents the position of the working lever and adapts synchronously to its motion. A blue ball pretends an optimal motion velocity by a circular motion over the motion range. The athlete can adopt his workout motion velocity by following the position of the oscillating blue ball with the needle. First tests verified that it is easily possible to the athletes to adopt to the predefined velocity. Especially for older persons a proper execution of the exercise is possible with less stops during exercise. An accurate workout is enabled by velocity preset and it is possible to develop on the workout for the user. The user interacts with a touch screen for which the user interface was optimized, e.g. by using large sized buttons and only minimal user input necessary. There are only two parameters necessary by the user, the workout weight and the oscillation velocity. These parameters are defined by steppers.

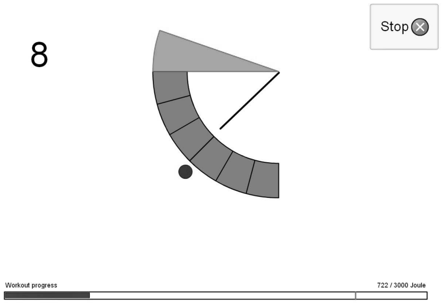

Fig. 5. GUI screenshot of the training screen. After logging onto the system with the RFID user card, the trainee has to perform the exercises in sync with a running ball. Initial tests have shown that even first time users can adapt their motion after three cycles (up-down) to the predefined speed. Remaining repetitions are shown on the left side. The red segment shows that the user in the last up movement was going up too high. At the bottom of the screen, the percentage of the training completed is shown. Then 100% are achieved, visualised by the small line in the progress bar, the trainee can continue the training if he is motivated enough. When the complete bar is filled, the system stops the training – additional training now is no longer advised. This is defined by the trainer.

The next iteration of the system will allow to connect multiple sensing systems to a low cost bare bone computer. For each training device, the minimum requirement is a card reader mounted at the device for trainee identification. Optionally, a small-scale touch monitor can be connected to allow especially novice user to get feedback on their training, e.g. accuracy of exercise execution. The GUI can also be located on the trainees personal training device such as a PDA computer that is wirelessly connected to the overall training system. It could be imagined that there are several systems only allowing high-valued customers to use this special service.

The complete system was realized using state patterns as shown in Fig. 4. This allows only transitions between defined states and thus in case of unexpected events never leaves the system in an inconsistent state. This e.g. includes untimely stopping of exercises as well as potential system failures.

The presented system is connected to the existing training and management system and thus can retrieve training plans and information when the trainee places his member card on the card reader of the training machine. This direct integration was easy to do as there were no vendor-specific user interfaces to deal with to acquire and process the sensor data.

III. DATA ACQUISITION AND MEASUREMENT PROCESS

A. Auto-Calibration of the Sensor Device

During prototyping, the sensors often had to be calibrated carefully and manually with long test series and time consuming procedures. Also, it was impossible for a normal fitness studio employee to manage. The manual calibration required a program to collect and analyse the sensor data to generate the calibrated sensor settings which was saved in absolute terms in the code. A change of the calibration data or the sensor, e.g. for a second prototype the sensor would have slightly different characteristics, required a recompilation of the code to potentiate the changes.

The developed algorithm for self-calibration works as follows. The system is collecting and storing each 1000 acceleration measurement data in horizontal and vertical position. It is thereby possible to determine the 0g and the 1g level of each axis. The data's average, which is equivalent to the expected value in practice, the variance and the root mean square deviation are calculated. Thereby it is possible to detect vibrations during calibration. If there is no clear main peak in the occurrence, and the root mean square deviation is to large, this could be easily detected and the calibration has to be repeated. If the vibration level is low, the pre-analysed data is saved. The calibration routine allows to detect in which way it was mounted to the axis and thus allows a "stick-and-go" approach. This is necessary to allow a non-technician to setup and install the system. The system automatically detects which axis is, in case of the Synchronous Training Machine, parallel to the level and which is perpendicular to it. A label on the box additionally visualises the correct mounting as backup.

B. Algorithms for Data Processing

First the acceleration data are averaged for the first time on the PIC over five values to smooth the coarsest noise. By sampling the data it is necessary to maintain a certain sampling rate. Each sensor type has a certain working frequency which specifies the maximum sampling rate. This sampling rate mustn't be crossed, because this results large variations otherwise. At the ADXL203 two certain condensers between the data conductor pathes and ground are needed that influence the sampling rate and have to be adapted to it. At this sensor device, 3.9nF are chosen to reach a sampling rate of 1260Hz on the sensor device. This results in about 8ms for sampling and about 5ms for data transmission to the computer by 115200 Baud. So a data rate of about 76Hz is reached. The PIC only measures the the acceleration values, averages them over five values and sends them to the server application. This application post-processes the values by a floating average over ten values. Then the angle is calculated by a simple tangent. All other data like velocity, with help of the timestamps, or work, by calculating the difference from the current angle and the last local extrema are calculated. All the postprocessing is done on the server application, because it has more resources than the PIC, especially the calculation of floating point arithmetic and long integers is much faster. The advantage of this two step data processing is a relative low development effort on the PIC.

There exists a trade-off between accuracy and latency. The more accurate the measurements are needed, the merrier values are needed for the floating average and the merrier larger is the delay. All this trade-off factors are optimised for this measurement system, which is developed, to reach an accuracy of more than 1°.

C. Converting acceleration in Joule

The raw acceleration data are worthless for the athletes. I.e. the current power, the athlete produces during workout has more significance for feedback. The user should do their exercises in an certain power range. A certain algorithm has been developed to calculate Joules from the acceleration data. First the acceleration data are converted to angle values of the machine's working lever which corresponds to the leg angle between femoral and shank. In a next step the current work needs to be calculated, which is then related to the timestamps to achieve power data. The current work is calculated by the height difference, which the weight overrides. By doing the exercise a second lever at the machine with the weight is actuated by a gear box with the working lever. The weight is lifted and lowered in a vertical circular way. For the work calculation the local extrema in height are necessary. They are found by a floating window which moves across queued angle values. The work results by the difference in weight height of the last extrema and the current angel. To gain current power values the work is correlated with the timestamps.

$$
\begin{aligned}
&acceleration\ x, y \text{ -> } angleAlpha = tan(x/y)\\
&extremaAngle(found\ by\ floating\ window), currentAngle\\
&currentHeight = leverLength * \sin(currentAngle)^{-1}\\
&extremaHeight = leverLength * \sin(extremaAngle)^{-1}\\
&deltaHeight = abs(extremaHeight - currentHeight)\\
&work = weight * 9,81 * deltaHeight\\
&power = work/(currentTime - extremaTime)
\end{aligned}
$$

Generally this conversion of acceleration data to power data is possible because of the exact measurement technique which is used here. In most real world applications it is necessary to process the acceleration data to other physical quantities which are more familiar to the current user's situation, especially for giving feedback.

IV. CONCLUSIONS AND FUTURE WORK

We present a novel sensor device for a great variety of sports devices that by today no measurement system exists for. The algorithms allow for fast and accurate data acquisition and processing. Acceleration information is converted to Joule, a unit of great importance for trainees. This conversion so far has not been reported on.

The presented system is currently produced in zero-series and under real-world evaluation in a sports school. Future development will concentrate on multi-sensor and multi-display integration on one host PC.

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