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# Coupled human-machine tele-manipulation

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## Abstract

Robots are primarily deployed for tasks which are dirty, dull, or dangerous. While the former two are already highly automated, many dangerous tasks such as explosive ordnance disposal or inspection in hazardous environments are predominantly done via tele-operation. Usually, such tasks require the manipulation of objects in a way that cannot be done reliably with automated systems. In this paper, we present a method to tele-operate the manipulator of a robot by transferring the operator's arm movement. The movement is recorded with inertial measurement units which can be sewn into clothing and need no external infrastructure like cameras or motion capture systems. The lack of intermediate user interfaces (e.g. joysticks) makes this control method very intuitive and easy to learn. We demonstrate this with two different NIST manipulation tests and as part of an integrated system for the ELROB robot competition.

*Keywords:*Mobile manipulation; Human-robot interaction; Inertial sensor units; Self-calibration; NIST

## 1. Introduction

For some time, robots have been able to mitigate the risk for relief units in dangerous environments by collecting data and providing intelligence. However, many situations require action to resolve a crisis, and being able to act without exposing personnel to immediate hazards (e.g. while closing valves or removing obstacles) is the main motivation behind mobile manipulation research. Typically, a robot will be equipped with a 6 DoF robot arm. Commercial robots as they are sold to bomb squads and relief units are controlled with some kind of panel with multiple joysticks and buttons. There is no widely adopted standard user interface design besides the manipulator

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Fig. 1. Taking samples in a possibly contaminated area is a typical application for tele-operated mobile manipulation.

being controlled in a joint-by-joint fashion. This mode of operation requires intensive training and is notoriously exhausting, meaning that incorporating a robot into a relief team is a costly endeavor. For a more widespread application, the usage of such robots, especially in stressful situations, has to be simplified.

Besides intelligent assistance functions, which can operate automatically in a number of situations, we developed an intuitive user interface to control a manipulator. With the help of inertial measurement units (IMUs), the movement of the operator’s arm is recorded and transferred to the manipulator. The technical basics for this control paradigm have been published earlier in [1].

In this paper, we briefly describe the technical solution of estimating the operator’s arm movement with IMUs without prior calibration and how circumvent the physiological limitations of the human arm to access the full operating range of a robot arm. The focus of the paper will be on describing how our control method has been tested and evaluated for its usability, learnability and accuracy. We describe the standardized tests for mobile manipulation as proposed by NIST and executed in a test center of the WTD 41 (Koblenz, Germany). Especially the training curve in a formerly unknown task was tested. Additionally we show an integrated robot system using the manipulator control within a competition challenge.

## 2. Related work

Tele-operated robots have to rely on the decisions of their operator. It is possible to enrich the information the operator gets from the robot with intelligent assistance functions. These will help the operator with their situational awareness and in the decision process, but the movement is in full control of the operator. Within the tele-operated manipulators, methods can be distinguished by their input devices, e.g. joysticks (some mentioned in [2]). From standard joysticks to those with force feedback, the boundaries to master-slave control mechanisms are fluid.

Master-slave approaches, which are a method to couple the input control with the manipulator movement, are rather old (e.g. [3]). Such approaches often rebuild a model of the manipulator at the operators working place, which allows quite accurate movements. Additionally, master-slave controls are able to provide the operator with haptic feedback. By this, more resistance within the master device might inform the operator that the manipulator is near to an obstacle, or it is possible to feel the structure of a surface (e.g. [4][5]).

In-between the stationary master-slave approach and the higher mobile joysticks, there are exoskeletons. These are wearable devices which provide a certain stiffness, e.g. by mechanical parts [6] or artificial muscles [7]. Their advantages are a very precise reconstruction of the human motion and, compared to the master-slave approach, less space is needed and a certain mobility is possible. But an exoskeleton always affects the way the operator moves and, thus, is not applicable if the operator should also do something else besides controlling the manipulator.

Motion capturing is another approach to control a manipulator by reconstructing human movements. (e.g. [8][9]). Approaches range from camera based motion capturing (with active or passive markers) to motion capturing with inertial sensors.

### *2.1. Motion capturing with inertial sensors*

Motion capturing for manipulator control is not a novel idea; a good overview over different capturing approaches is given in [10]. However, with our application for relief teams or bomb squads in mind, most of those techniques suffer from one or more of the following drawbacks: they are not portable, need complex calibrations, or need cumbersome exoskeletons.

To reduce the encumbrance of the operator, we decided to use inertial measurement units (IMUs) to measure movements of the human arm. These sensors have become very popular with many applications, such as action recognition in games [11] or detection of typical or similar patterns in medical applications [12][13]. IMUs are also used for partial motion capturing, where only special parts of the body, as upper limbs for example, are considered. Here, example applications are home rehabilitation systems [14][15][16] or robot controllers [8]. For tracking applications several systems based on fusion of inertial sensors and a variety of other systems have been introduced [17]. For full body motion capturing a portable system based on inertial sensors combined with an acoustic system was designed [18]. Since Nintendo introduced the Wiimote in 2006 a lot of applications were developed [19][20][21], while low cost sensors are available for mass market applications.

As IMU data is based on accelerometer measurements, it is quite noisy and subject to drift. Therefore, different techniques are introduced to minimize measurement errors. Kalman filters are popular if data from multiple sensors is to be fused [15][16][18][21], Monte Carlo optimization may help to improve the SNR for a single sensor [14]. A number of heuristics [8][17] are employed to determine the precise gravity vector, which is by far the biggest contributor to drift errors.

## **3. Intuitive coupled arm-manipulator control**

In commercially available robots, the state of the art of manipulator control is realized with joysticks, several buttons and a lot of training. In our opinion, this drastically limits the set of tasks a robot can execute, and may even lead to situations where operators expose themselves to hazards simply because using the robot manipulator would take too long. We postulate the following properties for a useful manipulator control:

- Easy to learn: This reduces the time to deployment for a robot. It entails intuitive access to the whole system, without long introduction to different operating devices.
- Easy to transport: Relief units have limited capacity for equipment, thus the manipulator control should be as light-weight and unobtrusive as possible.
- Robust: The system must be easy to setup and use, with as little effort as possible, since it is likely going to be deployed in a high-stress situation. This precludes time-intensive and/or error-prone calibration.

All these conditions are satisfied by our direct coupled arm-manipulator control, where the movement of the human operator is recorded by inertial measurement units and transferred to the robot.

### *3.1. Robust arm movement reconstruction*

IMUs provide absolute orientation and acceleration data. The former is used to reconstruct the operator’s movement, and the latter serves as calibration input. The orientation data is corrupted mostly by high frequency noise, which can be filtered with a standard binomial low pass filter such as [22]. The acceleration data must be integrated twice to obtain relative orientation changes. The noise in the acceleration data causes substantial drift in this estimate, which is minimized with a combination of three adjustments. First, high frequency noise is eliminated with a low pass filter. Second, the local gravity vector is estimated and removed from the data. Third, whenever possible, drift is eliminated using zero velocity updates [23]: as the sensors are applied to the operator arm, we know that if the orientation of all sensors remains constant, the velocity must be zero. Therefore, all residual velocities must be caused by drift. Whenever the sensors are not moved, we retroactively correct for this drift in the acceleration data trajectory since the previous zero velocity update, yielding a corrected trajectory which can be used to recalibrate the system.

The calibration is based on a somewhat simplified model of the human arm, consisting of four spherical joints connected by segments corresponding to upper arm, lower arm, hand, and fingers, respectively, and the sensor position on each of the segments. The model can be initialized from the operator's body height and sex; we use statistics from anthropomorphic studies to initialize the segment lengths accordingly.

The calibration proceeds as follows:

1. Record motion from acceleration data and orientation from the sensor output
2. Apply noise reduction
3. Compute arm trajectory given the current model parameters from the orientation data
4. Compare model trajectory to the motion estimate from the acceleration data
5. Update model parameters to minimize the error

Steps 3 to 5 are repeated until the model parameters converge. Then we expect that the model parameters are equal to the arm anatomy and the current sensor locations. The calibration does not require specific movements. Furthermore, we found that the calibration mismatch is typically very small. Therefore, it is feasible to perform the calibration while the system is in use. The operator will subconsciously adjust her movements to counteract the initial sensor misalignment.

### *3.2. Arm manipulator movement transfer*

Our current system setup is largely based on our previously published algorithm [1]. Our evaluation platform is a tEODor platform with a mounted telemax manipulator, both of which are products of the German company Telerob. The manipulator arm has seven degrees of freedom (six rotating joints and one telescope segment), with a total reach of 1.7 meters. Unlike a human arm, the "shoulder" joint is mounted horizontally.

The operator motion is captured using five inertial sensors (Xsens MT-x) which are integrated into a jacket (see figure 2 left). One sensor each is placed on the shoulder joint, upper arm, lower arm, hand, and fingers. The shoulder sensor acts as fixed point of origin (figure 2 right). All sensors measure absolute orientation and accelerations, which enables us to compute the relative locations of the sensors with respect to each other and retrieve the arm position relative to the operator's upper body. The exact pose is reconstructed using a kinematic model of the arm. In particular, the segment lengths of upper and lower arm are estimated from the operator's body height. As we cannot map the joint configurations one-to-one, we match the tool center points of both arms instead. Using the forward kinematics of the human arm, we can compute the location of the index finger tip. Using the reverse kinematics of the manipulator, we can map this location to the appropriate joint angles. Since the joint mapping is not unique, we resolve ambiguities by selecting the "closest" solution, i.e. the solution which requires the least movement of the robot arm. The operator uses a secondary controller in their other hand to trigger additional actions with button presses. The robot arm's grabber can be opened and closed in this manner.

In order to enable operator control without a direct line of sight, the robot transmits three video streams and a visualization of the robot arm's position to the control station. One camera is positioned within the grabber, the second on the first arm segment (closest to the base), and the third camera is positioned on a pantilt unit next to the manipulator. The three independent viewpoints help the operator gauging the arm position in relation to the environment. The pantilt unit keeps the tool center point in its field of view automatically, relieving the operator of this tedious task.

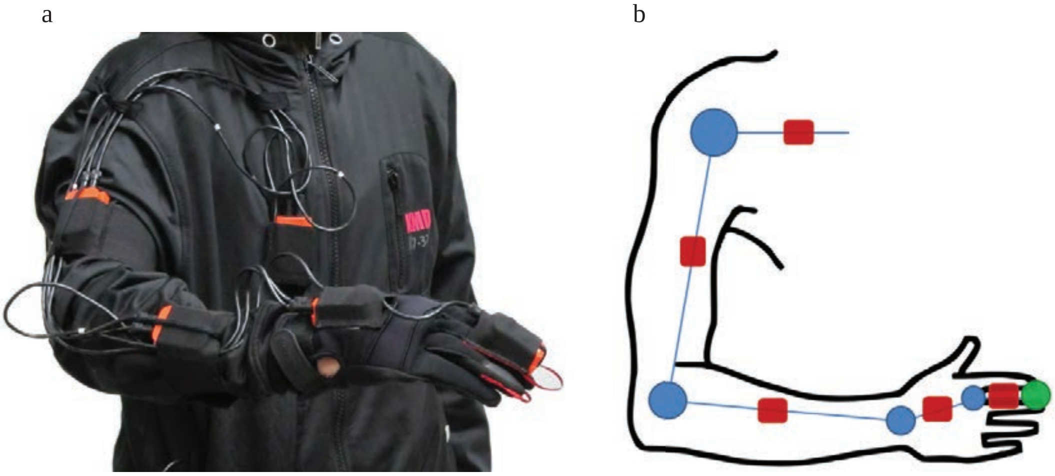

Fig. 2.(a) Real positioning of the sensors in a jacket. Here special sensors are used, but for relief units the sensors can be integrated invisible and without wires into jackets. (b) Positioning of the IMUs (red squares) to reconstruct the human movement. Shoulder, upper arm, lower arm, hand and fingertip build up a kinematic chain. The reconstructed position of the fingertip (green circle) is used to control the manipulator of the robot.

## 4. Experiments

In order to gain insight on whether the proposed manipulation control enables the operator to perform difficult manipulation tasks, we performed several tests. First we used a standardized test provided by the National Institute of Standards and Technology (NIST). This test includes various manipulation tasks designed to bring the manipulator arm and the control method to their limits. Further, we integrated the manipulation control into a robot system to participate in the M-ELROB trial 2014. This allowed us to demonstrate the usefulness of our approach in a scenario that was very close to real-world conditions in a rescue mission.

### *4.1. NIST manipulation standard test*

The last few years have seen extensive efforts to benchmark the abilities of different robots in a wide range of domains. On the one hand, several robot competitions have sought to compare different approaches and systems in specific tasks. RoboCup, ELROB, RockIn, Eurathlon, and the DARPA Grand Challenges are but a few to name. On the other hand, a lot of research has focused on establishing metrics to quantify the performance of parts and algorithms which are the building blocks of robotic systems. This is particularly challenging since many research robots are uniquely built and it is hard to perform tests in a way that is reproducible and allows comparisons of results from different groups.

NIST (National Institute of Standards and Technology) has advanced to one of the key players in developing tests for unmanned systems to benchmark even very different approaches and systems. The best-known of these tests is the mobility test on so-called “step fields”, which has been established as part of the RoboCup Rescue competition but become an independent test. The latest instalment of the mobility test sets – still in development – also includes tasks for mobile manipulation. It is intended to measure the abilities of the robot platform, the manipulator, and last but not least the usability by an operator.

The core of all manipulation tasks is the so-called “pipe star” (see figure 3 left), an artificial object of multiple pipes with vision test pattern hidden in each pipe. The manipulation task is passed if the operator is able to position the camera of the manipulator so that each vision test is readable. The pipe star can be mounted on different surfaces and heights and thus the test is adaptable to different robots (see figure 3 right). A test is typically performed as follows:

At first, the minimum and maximum working range is determined (red marker) as well as the most comfortable

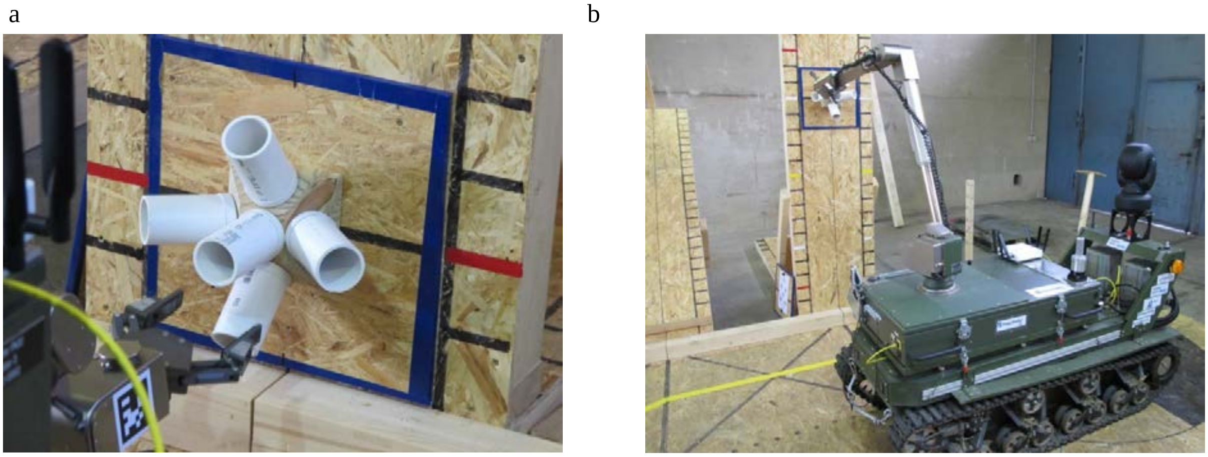

Fig. 3. (a) Pipe-star to test the abilities of the manipulator and the operator. Within each pipe an image of a visual test is hidden, which must be localized with the camera. (b) Robot during the NIST manipulation test. The pipe stars can be mounted on different heights.

working distance (yellow marker). The operator performs the test from each of those markers. The test is subdivided into a number of runs. Each run starts with the robot a few meters away from the pipe star. The operator has to move the robot towards the pipe star and inspect all pipes. Afterwards, the robot has to be moved back to the starting position, and once it has returned, the run is complete. The test objective is to repeat as many runs as possible within a 10 minute time limit.

Our operator is well acquainted with our control method but had never performed this test before. This enabled us to gain insight into how quickly a well-trained operator might be able to adapt to an unfamiliar task. At the very first trial, the operator managed four runs in ten minutes. By the sixth trial, the operator had increased their performance to ten runs in ten minutes. After the training phase, the operator could consistently perform nine or ten repetitions per ten minutes, regardless of the pipe star location. We believe this is indicative of the simplicity of our control method, which makes the manipulator control easy to use even at the operational limits of the hardware.

We also let a trained operator perform the same test with the standard off-the-shelf robot control, establishing a baseline performance. The operator, who was proficient both with the joystick control and the test, managed seven to eight runs per 10 minutes. Even though these tests lack rigorous statistical significance, we believe that they hint at the viability of our method and suggest that removing the joystick from the control loop improves the performance of tele-operated systems.

### 4.2. ELROB search and rescue scenario

The M-ELROB 2014 took place in Warsaw, Poland. The ELROB is a European robotic trial where different land based robots can show how well they are able to deal with real world scenarios. Those scenarios are mainly inspired from actual challenges in the safety and security domain. In 2014, we participated in the scenario “Search and retrieval of human casualties in outdoor environments.” The objective was to find an injured person (represented by a dummy) and transport it back to a safe position. The scenario was newly established at that ELROB, therefore the rules of engagement were somewhat lenient. For instance, there was no penalty for handling the dummy too roughly.

Our approach relied on a robot system that is comparatively small but powerful. We used a manipulator with our control method. All software was run with the ROS operating system and our multi-master extension, designed to make the system robust against temporary communication outages. We did not employ any autonomous functions and relied on the operator’s proficiency instead.

To move the dummy back to the starting position, we used a hook and a cable connected to the robot. As we expected the dummy to have some kind of equipment with belts, we aimed to hook up the dummy by its belt,

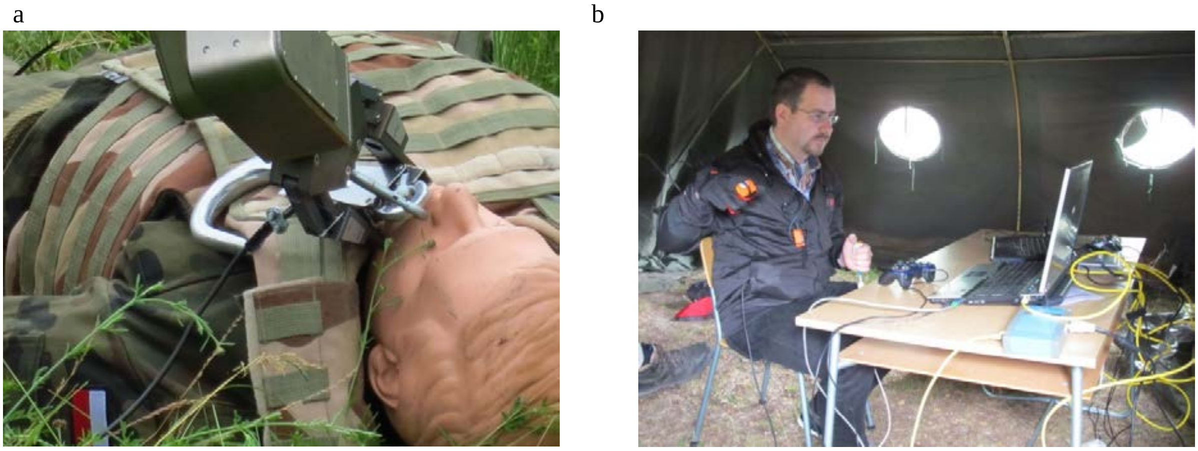

Fig. 4. (a) To drag the dummy out of the hazardous area, a hook has to be placed at the gear. This is a demanding manipulation task, which was easily done with the help of our manipulation control. (b) Operator during the ELROB task controlling the manipulator. The operator has no direct line of sight to the robot, so he has to rely on the video images. As our control needs no external infrastructure the usage in the field is no problem at all.

thereby being able to drag the dummy back to the safe zone. Our new control method was employed to place the hook in the vest (see figure 4).

According to ELROB rules, the scenario performance was measured by two criteria: The dummy weight, which could be chosen in advance as 10 kg, 35 kg, or 74 kg, and the time to complete the scenario. Additional points were awarded for finishing the scenario within half or three quarters of the total time limit. In case the scenario could not be completed in time, partial points were awarded for certain milestones, e.g. discovering the location of the injured dummy or moving the dummy at all.

We chose to rescue the heaviest dummy, as our robot is sufficiently sturdy to pull the weight. Switching between robot navigation and manipulator control proved to be unproblematic for the operator. Two cameras, one for scene overview and one for a close-up of the gripper, were sufficient to perform the manipulation task. The first attempt, taking 2:20 minutes to hook the garment of the dummy, was only partially successful as the hook mechanism did not latch completely. However, the operator was able to re-adjust the hook and return the dummy to the safe zone in 10 minutes. A second dummy could be located after minute 12 of the run. This time, the hook attachment went off without a hitch. The total operation time for the scenario was 22 minutes, which was the best time of all participants; the second-best performance took 29 minutes. This is also reflected in the final score of 3580 points (second place: 3250 points; third place: 3000 points). Additionally, several spectators commented that the manipulation movements of our system looked more natural and smooth compared to those of the competitors.

## 5. Results and conclusion

We were able to show in practical trials that our control technique is intuitive to use and works robustly. Only in a few exceptional cases, the robot arm has unexpectedly long movements, usually if the arm has to reconfigure when one of its joints reached its angular limit. As the human operator can adapt to the scaling between their own movements and the transferred manipulator motion, the sensor positions on the operator’s arm do not need to be very precise, negating the need for extensive calibrations.

Our control technique has been compared to the manufacturer’s joystick control using a standard NIST test at WTD 41 facility in Koblenz, Germany. The test showed that the motion transfer technique is very advantageous if a task requires multiple joints to be moved at once, as this is particularly taxing for a joystick operator. Untrained operators can perform tasks in roughly the same time with both controls, but our control technique is easier to learn. Two important weaknesses have been identified: firstly, the motion transfer activates more and different muscles in the arm than the joystick control. Therefore, it is considered quite taxing and requires adequate muscle training and/or frequent rests. Secondly, as the human arm’s motion range is smaller than the manipulator workspace, not all tasks which are theoretically possible can be solved with the motion transfer control.

After the trial, we improved the system with an additional pause button, relinquishing control of the arm and allowing the operator to reposition their fingertips. Once control is resumed, the manipulator arm will reset its frame of reference to the new pose, enabling the operator to increase her range by pausing and retracting her own arm. Also, the operator can ensure that her arm remains in a comfortable position for time-consuming manipulation tasks, thereby reducing muscular fatigue. Altogether, we strongly believe that the possibility to remove joysticks and similar devices from the control loop will substantially increase the range of applications for tele-operated manipulator arms. In future work especially the work with two manipulators is in focus. Here an intuitive control will again increase the operator’s versatility with manipulation tasks.

## References

[1] J. Hoffmann, B. Brüggemann, B. Krüger. Automatic calibration of a motion capture system based on inertial sensors for tele-manipulation. 7th International Conference on Informatics in Control, Automation, and Robotics. 2010

[2] S. Laycock, A. Day. Recent Developments and Applications of Haptic Devices. Computer Graphics Forum 22(2). June 2003. pp. 117-132

[3] R. Goertz. Mechanical master-slave manipulator. Nucleonics 12(11). 1954. pp. 45-46

[4] S. Tachi, H. Arai, T. Maeda. Tele-existence master-slave system for remote manipulation. Proc. of IEEE Conference on Intelligent Robots and Systems. 1990. pp. 343-348

[5] Y. Yokokohji, T. Yoshikawa. Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment. Proc. of IEEE Conference on Robotics and Automation. 1992. pp. 849-858. Vol 1

[6] M. Bergamasco, B. Allotta, L. Bosio, L. Ferretti, G. Parrini, G. Prisco, F. Salsedo, G. Sartini. An arm exoskeleton system for teleoperation and virtual environments applications. Proc. of IEEE Conference on Robotics and Automation. 1994. pp. 1449-1454. Vol 2

[7] N. Tsagarakis, D. Caldwell. Development and control of a soft-actuated exoskeleton for use in physiotherapy and training. Autonomous Robots 15(1). 2003. pp. 21-33

[8] N. Miller, O. Jenkins, M. Kallmann, M. Matari. Motion Capture from Inertial Sensing for Untethered Humanoid Teleoperation. Proceedings of the IEEE-RAS International Conference on Humanoid Robotics (Humanoids). 2004

[9] N. Pollard, J. Hodgins, M. Riley, C. Atkeson. Adapting human motion for the control of a humanoid robot. Proceedings of International Conference on Robotics and Automation. 2002. pp. 1390-1397

[10] G. Welch, E. Foxlin. Motion Tracking: No Silver Bullet, but a Respectable Arsenal. IEEE Comput. Graph. Appl. 22(6). 2002. pp. 24-38

[11] R. Slyper, J. Hodgins. Action Capture with Accelerometers. Proceedings of the 2008 ACM/Eurographics Symposium on Computer Animation. 2008

[12] A. Sabatini, C. Martelloni, S. Scapellato. Assessment of walking features from foot inertial sensing. IEEE Transactions on Biomedical Engineering 52(3). 2005. pp. 486-494

[13] M. Chang. Motion segmentation using inertial sensors. VRCIA '06: Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications. 2006. pp. 395-399

[14] H. Zhou, H. Hu, Y. Tao. Inertial measurements of upper limb motion. Medical and Biological Engineering and Computing. 2006. pp. 479-487

[15] H. Zhou, H. Hu. Upper limb motion estimation from inertial measurements. International Journal of Information Technology 13(1). 2007

[16] Y. Tao, H. Hu, H. Zhou. Integration of Vision and Inertial Sensors for 3D Arm Motion Tracking in Home-based Rehabilitation. The International Journal of Robotics Research 26(6). 2007. pp. 607-624

[17] E. Foxlin. Pedestrian Tracking with Shoe-Mounted Inertial Sensors. IEEE Comput. Graph. Appl. 25(6). 2005. pp. 38-46

[18] D. Vlasic, R. Adelsberger, G. Vannucci, J. Barnwell, M. Gross, W. Matusik, J. Popovic. Practical motion capture in everyday surroundings. SIGGRAPH '07: ACM SIGGRAPH 2007 papers. 2007. p. 35

[19] T. Shou, H. Gardner. A Wii remote, a game engine, five sensor bars and a virtual reality theatre. OZCHI '07: Proceedings of the 19th Australasian conference on Computer-Human Interaction. 2007. pp. 231-234

[20] J. Lee. Hacking the Nintendo Wii Remote. IEEE Pervasive Computing 7(3). 2008. pp. 1536-1268

[21] T. Shiratori, J. Hodgins. Accelerometer-based user interfaces for the control of a physically simulated character. SIGGRAPH Asia '08: ACM SIGGRAPH Asia 2008 papers. 2008. pp. 1-9

[22] J. Lee, S. Shin. General Construction of Time-Domain Filters for Orientation Data. IEEE Transactions on Visualizatiuon and Computer Graphics 8(2). 2002. pp. 119-128

[23] D. Grejner-Brzezinska, Y. Yi, C. Toth. Bridging GPS Gaps in Urban Canyons: Benefits of ZUPT. Navigation Journal 48(4). 2001. pp. 217-225