Adaptive Mesh Architectures for Speckled Robots

D. K. Arvind[1] **and A. P. Kulkarni**[2]

Abstract. The primary purpose of humanoid telepresence cyber-physical systems is to faithfully reproduce user intent in the remote robot. One of the main challenges lies in maintaining bipedal balance during complex behaviour such as walking, or negotiating obstacles whilst operating in a changing environment. The aim is to achieve this dynamic balance during human-controlled motion, and determine an effective solution to the humanoid telepresence problem by using a distributed sensing and actuation architecture. Preliminary results are presented for the stability of a Kondo KHR-1HV robot equipped with wireless motion capture Orient-2 sensors (each equipped with 3-axes gyroscope, magnetometer and accelerometer) for controlling six servos in the joints in the upper and lower legs and connected as a mesh, which demonstrate that distributed robotic control is better able to recover gracefully from command latency and local failures.

1 INTRODUCTION

Cyber-Physical Systems (CPS) [2] consist of physical resources which are coupled closely with networks of embedded sensor, actuator and computational devices for monitoring and controlling them. Examples of CPS include autonomous collision avoidance, robotic surgery, assistive technologies for pervasive healthcare, and tele-operations in hazardous environments. This paper considers the interplay between the low-level distributed sensing/actuation/computational devices and the higher-level control networks. The CPS of particular interest is humanoid telerobotics which seeks to achieve real-time use by a human operator of a anthropomorphic robot in a remote location. In a previous paper [1], the authors had described a specknet-based [3] cyber-physical framework for humanoid telerobotics.

Figure 1 shows a model of the humanoid telerobotics CPS consisting of a user interface for the operator which is realised as a distributed on-body sensor network for motion capture [4], a forward transmission link, a robotic “avatar” with mesh-connected sensor-actuator network, appropriate inverse kinematic mechanism translating user signals into avatar movements, and a reverse feedback link from the avatar to the operator.

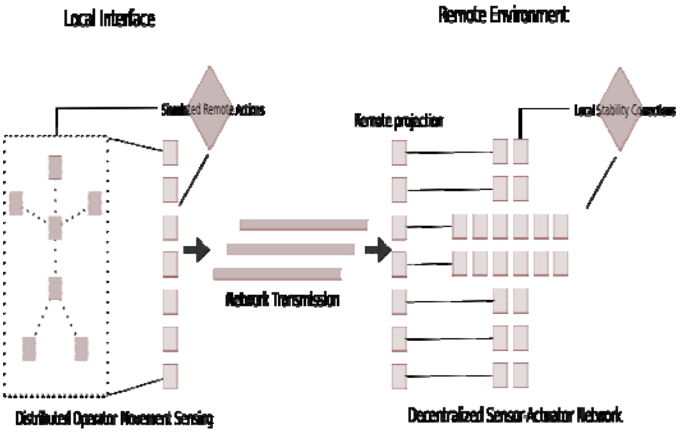


Figure 1. A distributed cyber-physical architecture for telepresence robotics. The human interface for the operator is realised as a distributed sensor network with the remote interface implemented as a mesh-connected sensor-actuator network [1].

One of the issues, when realising cyber-physical architectures, concerns the resolution of dynamic control; in other words, how does one maintain balance when making complex imitative motion, i.e. where in the control loop should low-level movement decisions be made?

The cyber-physical approach uses a distributed wireless sensor network on the operator, to sense movement at the source, and a sensor/actuator network on the robot to manipulate and control it. Three implementations were explored: distributed sensing with distributed direct actuation; distributed sensing with centralised actuation; and, distributed sensing with distributed cooperative actuation [1].

This breakdown corresponds naturally to three architectures for the management of low-level control schemes.

1. User-Side: Body-based wireless sensor networks on the operator detect local orientation of the limbs and

---

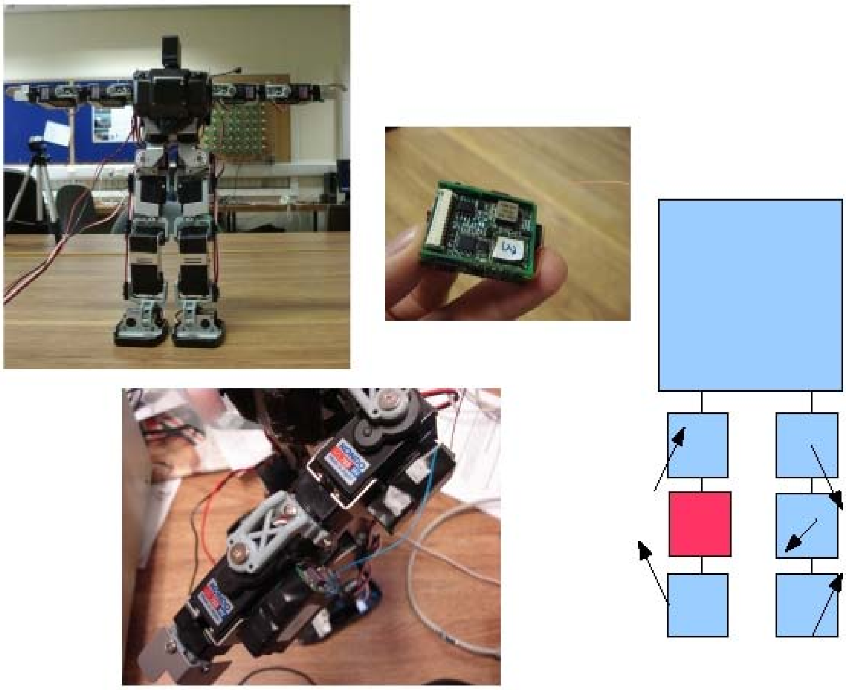
[1] Research Consortium in Speckled Computing, School of Informatics, Univ. of Edinburgh, EH8 9AB, UK. Email: dka`@inf.ed.ac.uk`.

[2] Dept. of Industrial Engineering and Operations Research, Univ. of California, Berkeley, CA 94720, USA. Email: anandk`@berkeley.edu`.

transmit these signals independently to the corresponding servos on the robot (point-to-point control).

2. Intermediate: Network-resident inverse kinematics programs on an intermediate layer between user and robot read movement information from the user and determine the low-level instructions sent to the servos. Predictive filters observe operator actions and transmit sanitised instruction data to servos for the purposes of protecting the robot from damage caused by motion outside its range or activating prerecorded movement patterns.
3. Robot-side: Individual wireless sensor-actuators devices on the robot's body accept input from the remote operator and come to a local consensus on how best to achieve user-transmitted goals, but make and execute these decisions locally.

Figure 2. From top-left, clockwise (1) KHR-1V robot, (2) Orient wireless sensor device, (3) local sensing, computation, and collaboration to active the servos to maintain balance, (4) Orient sensor connected to the servo on the robot.



In [1], the three schemes were evaluated on a theoretical model of the telerobotic CPS. In the case of the first scheme, the orientation of each Orient-2 sensor mounted on the body of the operator is mapped directly onto the movements of each servo. Using the model for evaluation with order-of-magnitude estimates of each quantity, even before substituting parameters in the model measured experimentally, it was observed that latency effects of a few decaseconds caused by dropped packets and transmission delays lead to failure [1]. It was concluded that distributed sensing with direct one-to-one control of each servo by body-mounted sensors is an inappropriate strategy by itself. In the absence of any additional local feedback, this method caused stability failure.

2. MESH-CONNECTED RECOVERY SYSTEM

It is proposed to investigate experimentally the third scheme outlined above, one of mesh-connected, wirelessly-communicating sensor-servos on the rigid body of the robot which co-operate to maintain its balance. Each servo/Orient combination communicates orientation information to its neighbours and decides its movement at each stage in response to the changing environment and external stimuli. As any servo deviates from the target position transmitted by its corresponding node on the operator's body, the surrounding servos on the robot-side respond to maintain dynamic balance within the system while remaining faithful to the individually targeted positions transmitted by the operator's Orient devices. Servos react fractionally in opposition to the movement of surrounding servos, with the goal of maintaining an overall stable position of the structure. The resulting mesh network of joint servo-sensors is more resilient to failures of individual servos and to the delays in commands reaching individual servos.

3. THE ORIENT WIRELESS MOTION CAPTURE SYSTEM

The Orient Motion Capture System [4] developed by the Research Consortium in Speckled Computing at the University of Edinburgh demonstrated for the first time, fully wireless, full-body, 3-D motion capture in real time using on-body network of fifteen custom-designed Orient inertial sensor devices. The system is free of infrastructure such as cameras[5][6], magnets, or audio receivers, and does not require special suits to be worn to contain the wires as in the cases of Xsens's Movens [7] and Animazoo's IGS-190 [8].

The compact Orient device measures 36x28x11mm and weighing 23gms (including the custom-designed Perspex casing and Velcro straps) and contains three 3-axes sensors: gyroscope, accelerometer and magnetometer and a temperature sensor. The nine sensors are sampled at a frequency of up to 512 Hz, and a positional update rate of up to 64 Hz is attained over the wireless network of 15 devices for full-body motion capture using a modest low-power 250 kbs radio. This is achieved thanks to an efficient local orientation estimation algorithm in the Orient device firmware which runs on a 16-bit dsPIC processor, and which reduces the communications data by 79% compared to existing methods [4].

Its onboard ADC is used to sample the inputs of the analog sensors: rate gyroscopes, magnetometers and accelerometers in each axis, plus temperature monitoring to allow compensation of the thermal response of the sensors. When multiple Orient devices are used together, their measurements are synchronised and their results transmitted across the radio channel in sequence, so that a complete frame's data can be assembled at the base-station within milliseconds. The base-station has USB, Bluetooth and WiFi interfaces which can bridge to a mobile phone or PDA for viewing the visual representation of the results.

The Orient devices capture orientation data at the maximum update rate of 64 Hz for 15 devices for around 150 minutes from a full battery charge. The 120mAh lithium polymer battery and charger are integrated into the device, with charging as simple as plugging in a lead, even when the device is held in a strap for use. The whole device can be placed into a low-power, sleep mode for weeks at a time, whilst being ready for use within a couple of seconds of being woken by a radio signal.

A simple calibration process requires the operator to hold briefly, just for a few seconds, a pre-determined stance which enables the alignments between the Orient devices and the operator's body segments to be automatically accounted for.

The MotionViewer software provides a user-friendly interface for the operator to interact with a network of Orient devices. The software comprises of five main subsystems: Device Interface, Forward-kinematic rigid-body model, Project Management, Real-time visualisation, and a Plugin API.

The Device Interface is used to configure individual Orient devices and set up a network to perform motion capture. The base-station with its USB, Bluetooth and WiFi interfaces acts as a bridge between the Orient devices and the host which could be a PC, PDA or a mobile phone. The interface is designed to be usable as a library for stand-alone applications, in addition to its use in MotionViewer.

4 EXPERIMENTAL RESULTS

In the following experiments, the operator is strapped with Orient devices for motion capture.

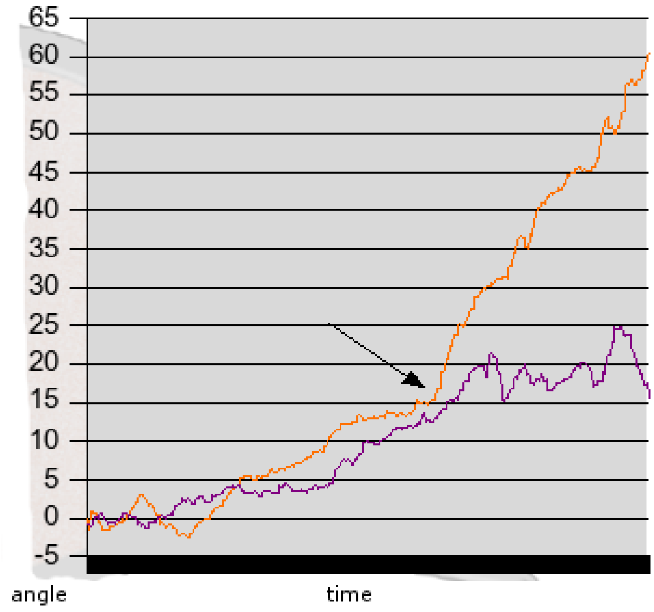


Figure 3. Graph of the angles of displacement of the torso (y-axis) of the robot over time (x-axis) for the two cases: with (purple, lower line) and without (orange, upper line) assistance of a collaborative mesh network. The arrow points to the moment when the robot topples.

The telerobot used in the experiments was a commercial off-the-shelf Kondo KHR-1HV [9] humanoid desktop-scale robot. The servos on the robot are almost identical and could be approximated to behave as a distributed robot application consisting of homogenous components. Each Orient sensor node directly controlled the orientation and motion of a single servo on the robot body. In order to simplify the hardware implementation, the effect of directly integrating the sensor node with the servo was simulated by routing instructions via a central computer connected to the robot. As the transmission speed of instructions from the robot to reach and activate the servos was negligible (less than a millisecond) in comparison to other latencies in the system, this simulation does not affect the authenticity of the results.

Early results are presented for testing experimentally the hypothesis outlined in the third scheme in Section 2 in which the Orient sensor devices on the robot-side collaborate locally to maintain its balance. The operator with the Orient sensors strapped to his body controls a remote robot with a decentralised network of Orient devices linked to the servos. Each sensor-actuator combination re-aligns itself to match positions with its counterpart on the user's body several times per second using simple update rules, which permits dynamic responses to the user's actions. In the absence of direct position instructions from the operator, the sensors communicate locally to maintain the balance of the robot. The resulting emergent behaviour based on the simple rule of making fractional movements in the servos in the direction opposite to their neighbours is in practice more resilient than external movement directives.

The effectiveness of the mesh-networked sensor-actuator combination was tested in maintaining balance of the robot due to unexpected environmental impact resulting in extended packet delays from the operator. An Orient device was also mounted on the torso of the robot to measure and record its angle of displacement from the vertical. Mechanical failure and packet losses were simulated by disconnecting the power supply to the Orient device in one of the sensor-actuator pairs on the robot's "knees". External pressure was steadily applied on the robot's torso until it toppled. This was carried out in two scenarios: with the sensor-actuator pairs collaborating as a mesh network; and with the actuators acting in the normal manner controlled by a single built-in gyroscope.

The angle of the robot's torso with the normal was plotted over time as a graph shown in Figure 3. The orange (upper) and purple (lower) lines refer to the cases of without, and with the mesh-connected collaborative network to maintain balance. Without mesh recovery the robot toppled quite rapidly at the point in time indicated by the arrow in the graph. In contrast, with the mesh recovery activated, the servos shared the neighbours' orientation data and moved fractionally in the opposite directions. The outcome as shown in the purple line is the neighbouring sensor-actuator pairs compensating successfully for the "failed knee" to maintain a temporary stable feedback loop with the angle with the normal being maintained steadily around 20 degrees. This preliminary result favours the idea of a mesh recovery telerobotic system for maintaining balance using local sensing and control while satisfying external movements sent by the remote operator.

5 CONCLUSIONS & FUTURE WORK

A couple of questions of theoretical interest immediately present themselves:

1. In the case of arbitrary rigid body structures, does there exist a set of rules for local responses for the servos that keep the system stable?
2. Is a meshed interconnectivity necessary for larger systems or is the awareness of the nearest neighbours sufficient?

The second scheme outline in Section 2 assumes the availability of information and data on the wider Internet in the humanoid CPS, as well as a large collection of possible users. An interesting inquiry would be to explore how this data can be used in the other layers to help smooth the telepresence experience. For example, access to online movement recordings and motion-capture databases may allow lower-level portions of the telerobot system to better coordinate its movements.

The ``physical" layer need not be isolated to the robot's end. More sophisticated interfaces might utilise distributed actuation on the operator's end in the form of wireless haptic devices.

ACKNOWLEDGEMENT

The authors wish to thank the Speckled Computing group at the University of Edinburgh for useful discussions. APK was supported by the Research Consortium in Speckled Computing during his visit to the University of Edinburgh during the period, July – December 2007. The Research Consortium in Speckled Computing is funded by the Scottish Funding Council as part of the Strategic Research Development Programme (R32329), and UK Engineering and Physical Sciences Research Council (EPSRC) as part of the Basic Technology Programme (C523881).

REFERENCES

[1] D. K. Arvind and A. P. Kulkarni. Specknet-based Cyber-Physical Frameworks, in Proc. Int. Workshop on Cyber-Physical Systems Challenges and Applications (CPS-CA'08), Santorini Island, Greece, June 11 2008, in conjunction with the 4th IEEE Int. Conf. on Distributed Computing in Sensor Systems (DCOSS'08).

[2] http://www.nsf.gov/pubs/2008/nsf08611/nsf08611.htm accessed on 1 March 2009.

[3] D. K Arvind, "Speckled Computing", Proc. 2005 Nanotechnology Conference, Vol 3, pp 351-4, ISBN 0-9767985-2-2, Anaheim CA, USA, May 2005, NSTI.

[4] A. Young, M. Ling, and D. Arvind. Orient-2: A Wireless Real-time Posture Tracking System Using Local Orientation Estimation. *Proc. 4th International Workshop on Embedded Networked Sensors*, Cork, June 2007.

[5] Vicon, http://www.vicon.com

[6] Motion Analysis Corporation
http://www.motionnalysis.com
[7] Animazoo, http://www.animazoo.com
[8] Moven, http://www.moven.com
[9] Kondo http://www.kondo-robot.com