ROBOTICS AND MACHINE PERCEPTION

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Bio-inspired solutions for locomotion through the gastrointestinal tract

This paper describes a bio-inspired approach to perform effective, smooth and safe navigation through the human body—and, in particular, through the gastrointestinal tract—with the goal of making new applications for endoscopy possible. In traditional colonoscopy, medical doctors explore the colon by pushing a flexible tube from outside and stretching the colon in order to open the lumen and to align the intestine with the colonoscope.[1] Microendoscopy (and wireless microendoscopy) should allow safe, painless and "natural" access to the hidden and remote regions of the human body for final diagnosis. It will do this by exploiting highly-autonomous micro-instrumentation capable of flexible locomotion.

For example, an inchworm locomotion device is made up of basically two clampers and one extensor. The clamper is used to adhere the device securely onto the locomotion environment, while the extensor produces a positive displacement, the stroke. One promising solution consists of a pneumatic bellow—which serves as the extensor—and two clamping mechanisms that suck the tissue and then grasp it by closing two opposite jaws (see Figure 1). However, in *in vitro* and *in vivo* tests, it was found that a purely mechanical approach cannot produce a real, miniaturized, autonomous, adaptable navigation system for the gastrointestinal tract. Early prototypes had problems related to the machine's inability to perceive the environment and to "react" appropriately.[2]

Such considerations have forced us to face the problem of navigating the intestine in an integrated way, by considering globally all problems related to the actuation, sensing, control, and mechanism. As with living creatures—even the simplest ones—the locomotion device must be designed as an integrated smart system.

Locomotion and adhesion: bio solutions
The most critical point in any locomotion mechanism is related to its adhesion to the terrain, where adhesion relates to friction, grasp and attachment. The strategies adopted in nature to perform locomotion rely on a wide variety of ingenious mechanisms such as dynamic adhesion, suction, adaptation to surface profiles, etc.[3,4]

An optimized interface—from the morphological point of view—between the locomotion device and tissue is not sufficient to reproduce an
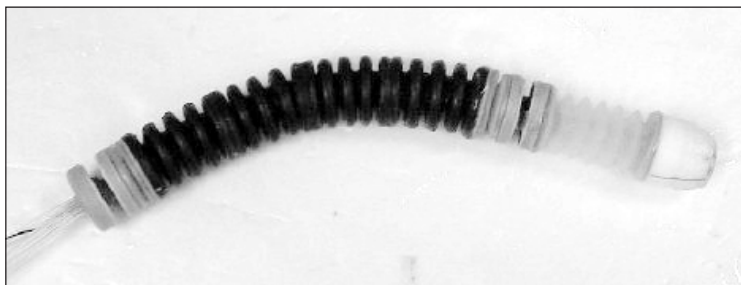
Figure 1. Inchworm device for semi-autonomous colonoscopy.

Editorial

Welcome to the first edition of the R&MP newsletter for 2003. This issue brings together a number of themes, including industrial applications, miniature robot systems, educational robotics and user interfaces.

Three articles develop the industrial theme, all expanding the range of robotics systems and techniques available in the industrial environments, and all illustrate the importance of technology integration for industrial application development. Carpanzo et al., describe the use of component software systems to create modular, reconfigurable components for shop floor manufacturing systems, offering greater scope for plant restructing and more options to cope when component systems fail. Albert et al. describe ongoing work on bipedal robots for service robotics applications. The article describes the integration of controls and sensing for reactive vision-guided walking. The third article, by Schlechter & Henrich, describes the integration of techniques for assembly planning and manipulation, and in particular the extension of these techniques to accommodate the manipulation of deformable objects.

Two articles report on innovative techniques in the area of miniature, biologically-inspired robotics. Lopez et al. describe the development of smart power integrated circuits for piezoactuators, and their use for both the mobility and manipulation systems in miniature robots. Menciassi et al, on the other hand, describe the fabrication of miniature locomotion mechanisms based on the tape

worm. This is exciting work, illustrating the ingenuity of nature, the scientific enterprise and the craft of the engineer.

The remaining three articles in this issue address internet-related aspects of human-robot interfaces. The article by Khamis et al. illustrates the growing area of online robots for education. It is becoming more apparent that online robots are an important new 'educational technology'. The article illustrates the technology components required to create a user-friendly educational environment and reports on student feedback following its use in practice. The article by Uberle & Buss focuses on advanced haptic devices for telemanipulation over the internet. The research aims to develop devices that provide high-fidelity feedback to their human operators. Potential applications include virtual manufacturing, telesurgery and virtual reality systems. The third article, by Koenig, describes a Java-based toolkit for web-based simulations of articulated robots.

We encourage you to read all the articles and to follow up the references for further details.

Finally, I would draw your attention to the recent fire at the Edinburgh University AI Library. This is an important historical landmark for AI and we encourage your assistance in restoring its collection.

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Contributing to the RM&P Newsletter

News, Events, and Articles
Contact our technical editor Sunny Bains (sunny@spie.org) with ideas for articles you would like to write or read. For full information on article submission go to: http://www.sunnybains.com/newslet.html

Special Issues
Proposals for Special Issues are welcomed and should include:

- A brief summary of the proposed topical area.
- The reasons why it is of current interest.
- A brief biographical sketch of the proposed Special Issue editor.

Special Issue proposals should be submitted jointly to Gerard McKee and Sunny Bains.

Upcoming Deadlines
12 May 2003: Ideas for articles you'd like to write (or read).

11 July 2003: Calendar items for the twelve months starting September 2003.

Fire at Edinburgh University AI Library: help needed to rebuild collection

As you may be aware, on 7th/8th December 2002, a fire swept through Edinburgh's Old Town, destroying many buildings, including 80 South Bridge, one of the four sites of the university's School of Informatics. Thankfully, no one was killed or injured. However, 80 South Bridge was home to the Centre for Intelligent Systems and their Applications, which includes the Artificial Intelligence Applications Institute. It housed the AI Library: an historic and unique collection of books, journals, technical reports and dissertations, many from the earliest days of AI research. This library was almost entirely destroyed in the fire.

We are extremely grateful for the many unsolicited offers of donations of books and papers that we have already received. They have inspired us to campaign to restore this invaluable collection. To do this we need your help. Many of the books and journals are no longer in print, and most of the dissertations were never published. Indeed, the AI Library was the archival repository of all AI PhD, MSc and UG dissertations and Departmental Re-

search Reports. Our priority now is to try and replace this knowledge base with electronic copies.

We are asking all AI graduates for copies of their dissertations, which we plan to digitize, and are also asking other Informatics graduates and friends around the world if they are able to help. Please let us know if you have any AI books or papers that you would be prepared to donate to the new Library by logging on to the web address given below. *Please do not send copies yet.*

It is crucial that we contact all our former students, so please pass this message on to any Edinburgh graduates who may not be aware of the impact of the fire.

Thankfully, the building along with the contents of the library will be covered by insurance. However, to prevent a loss like this in the future, we intend to create a digital archive of the documents we receive. This would also ensure that the AI community worldwide could access much of this knowledge base online. Please send a donation today to help make this

possible.

Cheques should be made out to *The University of Edinburgh Development Trust*. They should be sent to:

AI Library Appeal
The University of Edinburgh
Charles Stewart House
9-16 Chambers Street
Edinburgh, EH1 1HT, UK.

We appreciate your help.

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Manipulating deformable linear objects: programming using manipulation skills

Deformable linear objects (DLOs) such as hoses, cables, and leaf springs can be found in many industrial products. Automation of production processes involving DLOs is complicated because of the object's deformability and high manufacturing tolerances. Solutions can be found for specific tasks by means of special hardware or complex programming of sensor-based software. However, in general it is difficult to adapt such inflexible solutions to other, even quite similar situations.

To solve this problem, Henrich[1] developed a formal model to describe assembly tasks involving DLOs. The DLO consists of an edge (E) and a free vertex (V). The environment is modeled by convex polyhedrons consisting of vertices (V), edges (E) and faces (F). All contact states between the DLO and obstacle primitives, and all possible single-contact state transitions, are depicted in Figure 1.

For the manipulation of rigid workpieces, Hasegawa[2] introduced the concept of *manipulation skills:* small, robust, sensor-based programs that can perform some common, recurrent, clearly-specified tasks. However, there are no skills that handle deformable objects.
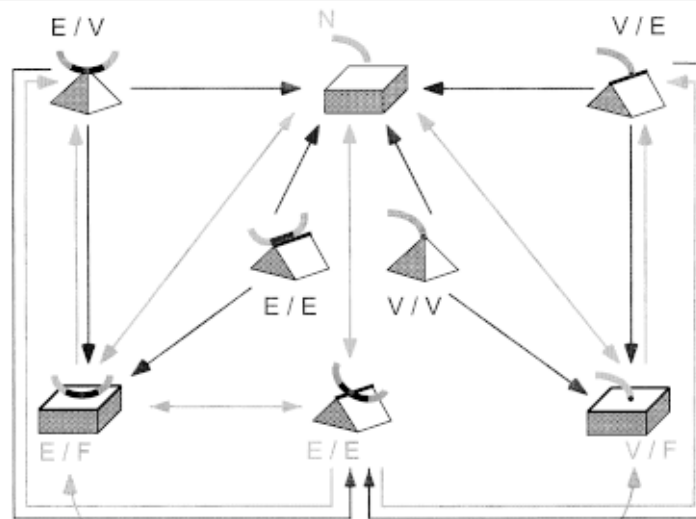

Figure 1. Shown are all single-contact state transitions between a DLO and its convex polyhedral environment. Initiated transitions are shown in grey, spontaneous transitions in black.[1]
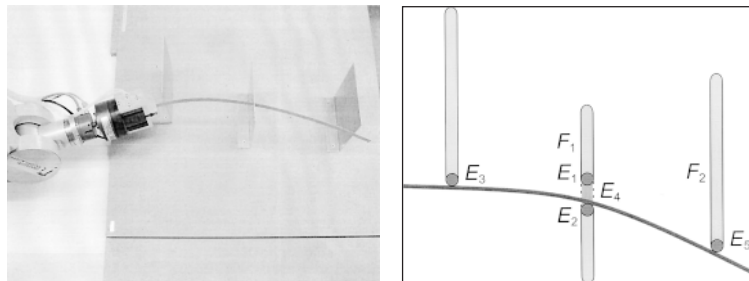

Figure 2. Target state of leaf spring assembly. Left: overview. Right: horizontal section with designation of the involved faces and edges.

Manipulation skills

Given an assembly task for automation and its description by contact state transitions, the executing robot system still has to deal with uncertainties, oscillations and precise, intentional, deformations of the workpiece. The following three types of manipulation skill have been developed in order to solve these problems in detail:

1. Given a desired single contact state transition, together with a robot trajectory leading to this transition, an appropriate skill should stop the robot motion at the time of transition with the least possible delay. A set of force-based skills for all single-contact state transitions with purely translational robot motions was implemented.[3]

2. During assembly processes, undesired DLO oscillations may occur. Since the natural decay time is generally quite long (e.g. >45 sec. for leaf springs), the total assembly time may be reduced by using active damping operations. Adjustment motions can be used to stabilize the manipulated DLO after just a few oscillation periods. All required parameters can be determined from measured forces and moments.[4]

3. In some situations, objects have to be elastically deformed in order to achieve a desired shape. Given the contact points along with the desired tangent directions and translations for each contact point, an appropriate robot trajectory can be generated using different kinds of splines for shape approximation.[5]

Leaf-spring assembly

As an example of the application of these manipulation skills, Figure 2 shows a leaf spring 50cm long by 2cm wide that must be clamped between three parallel plates that are 19cm high, 15cm wide, and 20cm apart. The notch in the middle plate is 6cm high and 1cm wide. Misalignment of the plates prevents the spring from being mounted without deformation. In terms of contact states, the goal situation can be described as $E/E_2 \wedge E/E_3 \wedge E/E_4 \wedge E/E_5$, with the designation of edges and faces as shown in Figure 2.

For this task, all three types of manipulation skill are needed. Without the intentional deformation skill, the assembly is impossible. This skill is likely to fail without sufficient knowledge of its starting situation, which, due to uncertainties, can only be achieved robustly using contact state transitions. Without active damping of the oscillations after a fast pickup, insertion from above between the first two plates might be unsuccessful. Additionally, oscillations disturb the force-based contact state transitions.

The transition skills require a 5s initialization in order to achieve robust detection with an average delay of 0.5s. With robot speeds of 5-15mms^{-1} during transitions, 100mms^{-1} between transitions, and a pickup speed of 50% of the maximum, a complete assembly takes about 1min 40s. Out of 25 trials in series, two (8%) failed at damping after pickup, eight (32%) were successful although the insertion in the notch was not recognized, and the remaining 15 (60%) were faultless.

Conclusion

Programming with manipulation skills is easy, flexible and robust. Manipulation skills are now available to perform: a sensor-supervised contact state transition; an object deformation without manual search for an appropriate robot trajectory; and active damping to reduce long,

Development of self-reconfiguring manufacturing control systems

Reliable and flexible automation systems are crucial for the competitiveness of modern manufacturing systems. Re-usability and reconfigurability of developed control solutions are also fundamental in order to reduce the cost and time necessary to design and realize a new production systems, or to modify existing ones.[1,2] Furthermore, intelligent control systems—which can self-reconfigure according to varying operating conditions and to deal with non-nominal situations by means of suitable fault diagnosis and recovery methods—are also key for modern industrial plants. Here we discuss a structured development methodology for the design of manufacturing control systems that achieve these objectives. In particular, formal reference models—based on the object-oriented paradigm and compliant with international standards—are exploited to guarantee interoperability and interchangeability.

Development methodology

The adopted methodology is based on the following major design phases.

1. System definition: the process to be automated is described, and both the activities to be performed and objectives of the automation system are defined.
2. Control system specification: the tasks and the essential functions of the supervision and control system are defined.
3. Control system design: the supervision and control system are developed through suitable formal reference models for both the architectural and functional design.
4. Control system integration and testing: the system is checked by means of formal analysis and/or simulation methods to make sure that the designed control functions meet the requirements.
5. System integration and testing: control code is generated to check whether the control system works on its devices, and to see whether all the system's requirements are met.

Reference models

To define the reference model for the control system architecture, different international standards for the representation of open control systems architec-
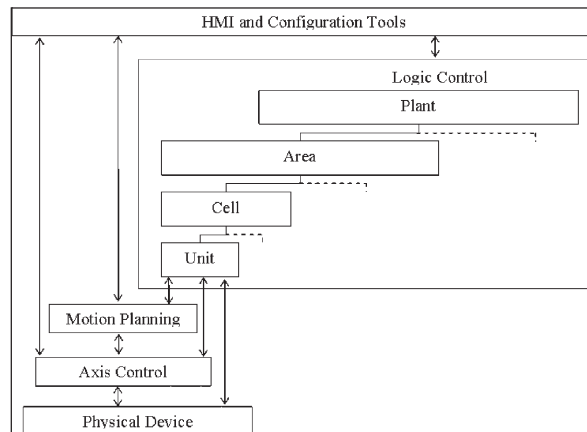

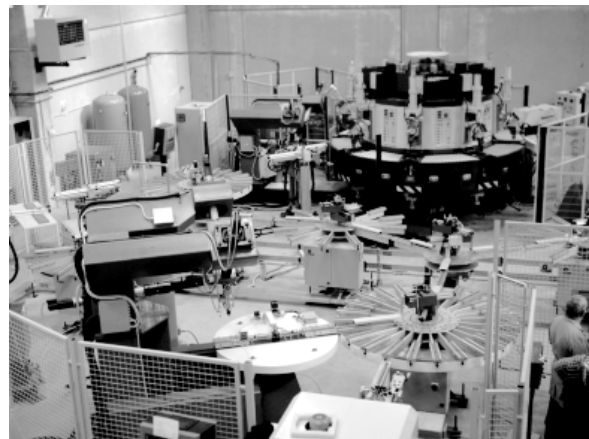Figure 1. Reference model for the control system architecture.
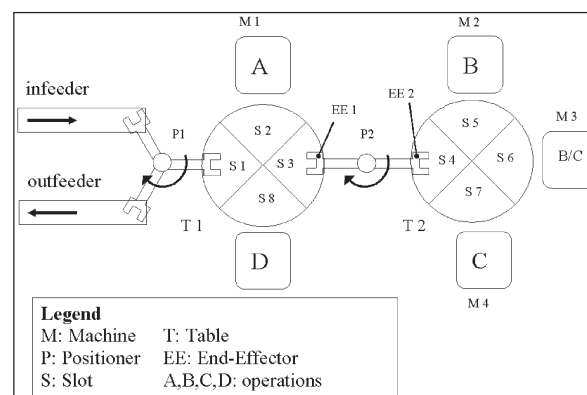

Figure 2. Flexible shoe manufacturing plant.

Figure 3. Cell layout.

tures—OSACA, OMAC and OSEC[3]—have been taken into account. Since such standards are not compliant with each other, a new reference model is adopted that exploits their commonalities: its basic modules (HMI and Configuration Tools, Logic Control, Motion Planning and Axis Control[1]) are illustrated in Figure 1.

The IEC 61499 standard is used for the functional design. This standard is based on a fundamental module, the function block (FB), that represents a functional unit of software. A FB is characterised by the following: sets of event inputs/outputs and data inputs/outputs; internal data; an execution control chart (ECC) consisting of states, transitions and actions; and a set of algorithms associated with the ECC states. The execution of algorithms is invoked by the ECC in response to event inputs. When the execution of an algorithm is scheduled, the needed input and internal data values are read and new values for output and internal data are computed. Furthermore, upon completion of the execution of an algorithm, the execution control chart generates zero or more event outputs as appropriate. By properly connecting more FBs an application can be defined.

The models considered here are based on basic object-oriented modelling concepts like modularity, hierarchy, encapsulation, aggregation, and inheritance. The benefit of adopting such models is that the definition of even complex control systems is simplified, reusability is improved, and reconfigurability is enhanced.[1]

Application example

This framework has been applied to the design of the control system for a manufacturing cell in the flexible shoe manufacturing plant shown in Figure 2. The cell considered is shown in Figure 3. The automation system has been designed using the reference models previously introduced: specifically, the control system architecture has been defined according to the reference model depicted in Figure 1, and the control system functional model has been designed through the IEC 61499 standard formalism.

Since different type of shoe models

Towards haptic interfaces for general-purpose applications

In recent years, human system interfaces have increasingly included haptic interfaces in addition to multimedia: 3D VR graphics and sound. Numerous, mostly highly-specialized force- and touch-feedback devices are being developed at educational and research institutions. Current commercially-available haptic displays include: low-cost devices for entertainment, e.g. force-reflecting joysticks, steering wheels, and mice; highly specialized devices for particular applications, e.g. the Laparoscopic Impulse Engine (Immersion Corp.); and general tool-based interfaces with low dynamic properties but a comparatively small workspace and low force capability, e.g. the PHANToM (SensAble Technologies), DELTA Haptic Device (FORCE dimension), and VIRTUOSE 6D (Haption). There is enormous application potential for haptic interfaces: e.g. in virtual manufacturing, medical and surgical VR systems, telesurgery, telemanipulation, telemaintenance, and e-commerce.

In the Control Systems Group, Faculty of Electrical Engineering and Computer Science, Technical University Berlin (TUB) headed by Prof. Martin Buss, a key research topic is high-fidelity multimodal human/system interaction for VR and teleaction (telemanipulation) applications. Particularly, the group is interested in advanced control of haptic devices and teleaction/telerobotics over the internet including quality-of-service communication control issues.[1-3]

Our research and development efforts are aimed at a family of general-purpose haptic interfaces that can be used in a variety of applications. The key design objectives are a large workspace and high force capability. If, for the particular application, a smaller workspace, smaller forces, or a specific kinematic constraint—e.g. rotation of a tool around an incision point, as is the case in minimally-invasive surgery simulations—is required, the universal haptic display is constrained to these characteristics by a suitable control algorithm. Such (nonlinear) control strategies are a challenging research issue in themselves, and can substantially improve the performance of haptic displays. Developed haptic devices can be augmented by tactile feedback actuators for improved, high-frequency, vibrotactile feedback.

The key goal of universal applicability has lead us to create a bench-marking test-bed for developing novel haptic applications and performing the necessary feasibility studies. Once feasibility is verified and required characteristics during haptic interaction are identified using the general purpose devices, a tailored, highly-specialized, haptic device can be de-
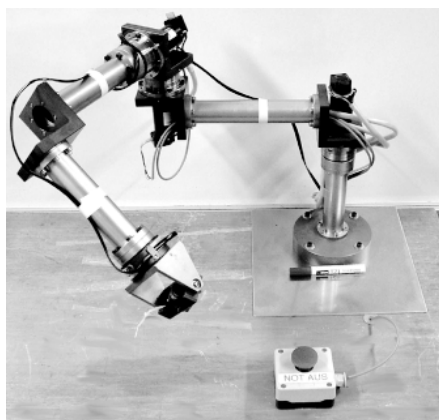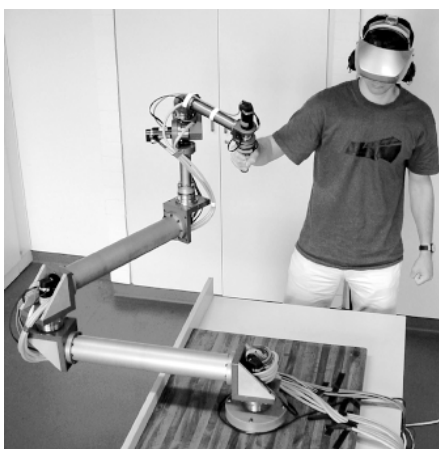

Figure 1. VɪSHᴀRD3.

Figure 2. VɪSHᴀRD6.

signed with exactly matching mechanical properties.

Prototypes

The objective of the prototypes we have developed, the VɪSHᴀRD family (*Vi*rtual *S*cenario *Ha*ptic *R*endering *D*evice), is to provide a haptic interface that can be used in various application domains including direct interaction between the operator's finger or hand and the virtual environment. To achieve this goal, the prototypes can be equipped with different interface tools (e.g. surgical instruments, possibly with additional degrees of freedom) or other devices (e.g. tactile actuators, exoskeletons for the operator's hand, small kinesthetic desktop devices) mounted at the end-effector. Due to these potential extensions, the design of our prototypes is strongly influenced by considerations of high payloads. To realize high-force

tasks and interactions with large environments, high-force capability and large workspace have been considered key design objectives. It is obvious that satisfying these requirements will tend to a degradation of the device's dynamic properties. Consequently, it is not possible to achieve an accurate haptic feedback by open-loop feed-forward control. Instead, active force (and acceleration) feedback control is required to shape the haptic interface dynamics as needed.

In Figures 1 and 2, the prototypes developed at the TUB are shown. VɪSHᴀRD3 is a kinesthetic desktop device with three active degrees of freedom. The end-effector is a gimbal-mounted thimble so that forces in arbitrary directions, but no torques, can be exerted on the operator's fingertip. VɪSHᴀRD3 shows good results regarding workspace ($60\times31\times31\mu m$ in width, depth, and height) and force capability (peak force larger than 87N in the entire workspace). Its successor, VɪSHᴀRD6, provides force and torque feedback in six degrees of freedom and an increased workspace ($86\times31\times31\mu m$; 360˚, 90˚, 360˚ in roll, pitch, yaw) and output capability (peak force: 178N). The weight of the moving parts is appproximately 19.7kg, which is much less than the weight of the industrial robots often used for haptic applications that require a large workspace and high force capability. More details about performance measures of VɪSHᴀRD6 can be found in a recent publication.[3]

To realize the comparatively large workspace of these prototypes, we decided to use purely serial kinematic designs, as parallel kinematics usually result in a significantly smaller workspace. Both devices have their first joints arranged in a SCARA-configuration with vertical axes avoiding the need for active gravity compensation. Thus, it is possible to mount significant payloads at the end-effectors: approximately 6.5kg on VɪSHᴀRD3 and 8kg on VɪSHᴀRD6. The required torque capability is provided by 150W DC-motors coupled with harmonic drive gears. These offer the advantage of zero backlash, light weight, high torque capability, and high single-stage ratios. To realize active force feedback control of the device, a six-axis JR3 force-torque sensor is placed between the tip of the robot arm and the end-effector.

Conclusions and perspectives

Our VɪSHᴀRD family of general-purpose haptic displays provides a testbed for the evaluation and development of novel, future applications in the area of haptic/multimodal VR and teleaction systems. The devices have large workspace, high force capability, active force feedback, and sophisticated control strategies to provide high-fidelity haptic feedback to their human operators. Future work will augment

Miniature robot based on smart piezoactuator units: MINIMAN-V

The manipulation of biological cells, assembly of MEMS, positioning of lenses in high density storage systems (DVDs), etc., are just some examples of tasks in which a high degree of precision in the manipulation and positioning of the objects is necessary. Currently, one of the most important fields of research is application of autonomous robots to high-precision tasks in fields like biology and medicine.[1] The use of miniaturized robots is one approach to achieving high precision for specific instruments: the Nanowalker project[2] and the MINIMAN-robot[3] are examples of this.

The goal of the project described here has been to develop a robot of dimensions around 1cm^3 to move with a maximum speed of up to 1cm/s and an accuracy of 10nm. This robot, MINIMAN-V, is based on piezoelectric elements as is described in Reference 2. The robot's structure is based on two piezoelectric platforms[3,4] depicted in Figure 1: one to position the robot and the other to perform manipulations. The robot will come equipped with micro-tools, such as grippers, to enable it to manipulate small objects. Eventually, we hope to consider even more complex machines that incorporate interface sensors to bridge the gap between the robot and the molecular world.

Our autonomous platform will form the basis for future systems, where microrobotic agents will be designed to perform cooperatively and their collective performance analyzed during micro-operations.

Onboard electronics

Usually, high voltages have to be applied to piezoelectric actuators in order to achieve large strain. We use special multi-layer piezoceramic actuators[4] that only require up to 50V. Thanks to this voltage reduction, an embedded solution is feasible, with the micro-robotic actuators and electronics based on integrated, smart, power circuits.

The micro-robot MINIMAN-V consists of two piezoelectric platforms, one for the motion unit and another for the manipulation unit. The latter controls the position of a ball that will host the micro-tools. Six piezoelectric actuators[4] form these platforms and four electrically separated regions[5,6] form each actuator.

Since there are 12 unit actuators (or legs), the architectural concept behind the onboard microelectronics was simply to define the same integrated circuit unit for each leg. Standard solutions based on CMOS technologies cannot withstand the required level of voltage, so hybrid components were considered. However, the size of these circuits made their implementation on the piezoelectric platforms difficult. Instead, us-
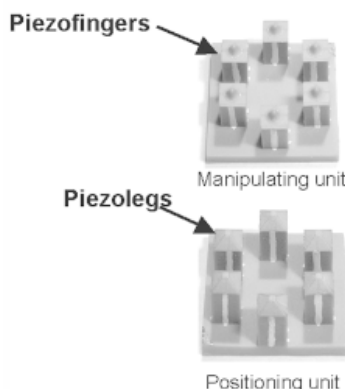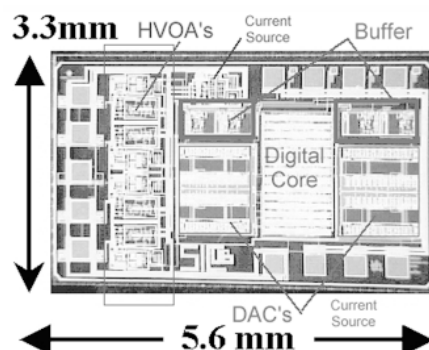

Figure 1. The two micro-robot platforms.

Figure 2. Diagram of the robot's integrated circuit.

Figure 3. Miniature robot after final assembly.

ing multi-layer piezoelectric actuators[5] and a commercially-available Bipolar-DMOS technology, we developed a suitable onboard driving solution.[6,7] The ability to integrate the high voltage analog circuits and the low voltage digital circuits on the same IC substrate allowed us to develop the Smart Power Piezoactuator Unit (SPU) concept.[6]

A digital control circuitry block was integrated with the HV (high voltage) blocks, defining an AMS (analogue mixed-signal) IC, see Figure 2. This circuitry has to work with the external serial control protocol[4] and generate the signals that used by the mixed-signal cir-

cuitry. Four power drivers can operate at high voltage conditions and drive the high capacitor value.[7]

To assemble the onboard electronics and piezoelectric platform units, the ICs were placed on two rigid PCBs.[5] A flexible PCB was then used to define the connections between the piezoceramic unit and the rigid PCBs. Just six external wires are used to connect between the two platforms. A photograph of the completed miniature robot is shown in Figure 3.

Conclusions

A miniature robot of 1.5×1.5cm^2 has been developed as a first attempt at a machine to be used in nano applications. The system is based on the concept on the Smart Piezoactuator Unit, which is defined by its piezoactuators, and its onboard Smart Power Integrated Circuit. Each IC is formed by a digital control system, based on a serial protocol to reduce the number of external wires needed, and four high-voltage operational amplifiers. The assembled microrobot requires only six wires, has a theoretical accuracy of up to 10nm, and a maximum speed of 0.7mms^{-1}.

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6. M. Puig-Vidal, P. Miribel-Català, J López-Sánchez, E. Montané, S. A. Bota, J. Samitier, U. Simu, and S. Johansson, *Smart power integrated circuits to drive piezoelectric actuators for cm^3 microrobot syste,* **Proc. SPIE 4334,** 2001.
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Software architecture for internet mobile robotics

Remote laboratories can be used to provide experiments essential in robotics education. Here, the user and laboratory equipment are geographically separated but linked via telecommunications. Such labs have the advantage that they are not restricted to synchronized attendance by instructors and students: thus they have the potential to provide constant access whenever needed by student. Many such remote facilities can be put together to provide a virtual laboratory, a framework that can be used to provide a coordinated set of experiments for students with hardware physically spread over different locations, but accessible via the internet. IECAT[1] (Innovative Educational Concept for Autonomous and Teleoperated systems) is an example of a virtual laboratory in the field of mechatronics and telematics. This article summarizes our contribution in this project.

Software architecture

Building a remote laboratory in the field of mobile robotics requires expertise in a number of different disciplines: internet programming, telematics, and mechatronic systems, for instance. It must perform "live", not just provide virtual reality or other types of simulation. Also, an intuitive user interface is required so that inexperienced people can control the robot remotely. The proposed architecture has three tiers, as shown in Figure 1.

Client tier

The user interfaces are designed based on the visual-proxy architecture—which is in some ways a specialization of the Presentation/Abstraction/Control (PAC) architecture[2]—to guarantee a high degree of extensibility and reusability in the software components. This architecture is intended to entirely separate the generation of the user interface from the abstraction-layer object.

To deepen and apply learned systematic knowledge of mobile robotics, the student may take advantage of three tutoring tours. These are classified according to the level of guidance into fully-guided (demo) tour, guided tour
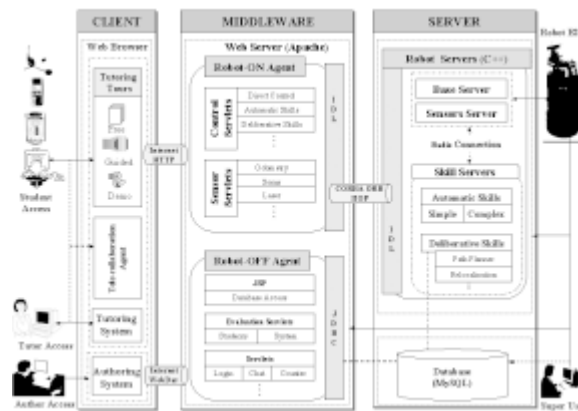

Figure 1. Software architecture for the virtual laboratory.
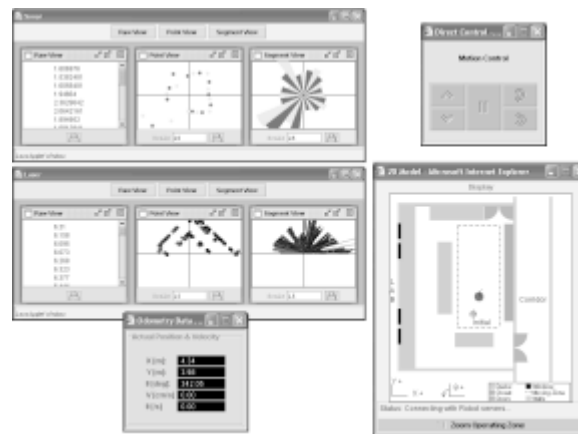

Figure 2. Sensory-data acquisition screen-shot.

and a free tour where the user can navigate around the virtual laboratory and pick up information at will. A telecollaboration agent provides the users with synchronous and asynchronous communication mechanisms and the authoring system enables mobile robots experts to define, modify or remove their own tutoring processes using the Web Distributed Authoring and Versioning (WebDav) protocol.[3]

Middleware tier

In this layer, an Apache web server hosts two agents. The *robot–on agent* deals with the real robot when it is actually running, providing the information required to enable any functionality required by either the user or during the guided or free tours. The agent contains two groups of java servlets: control servlets that send control commands to the robot; and sensor servlets to invoke the sensory data. The communication between these and the remote robot servers is done via the Object Request Broker (ORB) of the Common Object Request Broker Architecture (CORBA).

The *robot-off* agent represents systematic knowledge of mobile robotics by accessing a database using Java Data Base Connectivity (JDBC). This agent also contains many servlets such as evaluation servlets, login servlets, etc...

Server tier

Three C++ servers—*base* to send control commands to the actuator, *sensor* to provide sensory data, and *skill*—and a database comprise the server tier. A skill represents the robot's ability to perform a particular task. The skill servers are implemented based on a two-level control architecture called AD (Automatic and Deliberative levels) proposed by Barber.[4] The deliberative level is associated with reflexive processes that require a long calculation time as a consequence of reasoning. The path planner, the environment modeller, and the task supervisor are all skills that can be found in this level. The automatic level is formed by skills that interact with the sensors and actuators, and that require minimal time to process information.

Implemented experiments

The architecture described has been used successfully to implement the following indoor mobile robotics experiments accessible via the internet:
- Environment perception using multisensor data (laser and sonar);
- Direct motion control using PCs, PDAs, mobile phones, and voice tags;
- Remote activation of movement skills (go to point, rotate, obstacle avoidance, wall following, etc…);
- Environmental modelling and robot localization using sonar data;
- Generic tools, which the user can exploit to customize the experiment according to his/her needs. Such tools include a 2D model of the robot and the lab, odometry data panel, sonar data panel, laser data panel, motion controller and low-level programming editor. Figure 2 shows a screen-shot for a sensory data-acquisition experiment.

The remote laboratory was used last academic year (2001-2002) in a postgraduate course about intelligent autonomous robots. Student responses to using it to supplement course lectures were uniformly positive. Most felt that the online experiments helped them to achieve a deeper and more thorough understanding of the material. To evaluate network performance and response time, the system has

Table 1. Response time

Location	Min. (ms)	Max. (ms)	Av. (ms)
Spain	121	137.76	127.2
Germany	273	354	293.51
United Kingdom	394	2444	1157.45

FastScript3D: A JavaScript companion to Java3D

FastScript3D is a web-friendly companion to Java3D that makes it easy to get started using Java3D via JavaScript and HTML. FastScript3D has it roots in robotics as it was originally developed to provide 3D graphics capabilities for a spacecraft dynamics simulator tool at JPL. Since then it has been adapted to general purpose use for construction of 3D web page content.

The benefit of FastScript3D is that it allows you to quickly and easily create Java3D web content without having to be an experienced Java3D programmer. The language consist of a series of simple commands for loading, animating and controlling the 3D scenes from JavaScript. The system is written to be easily extended: for instance, allowing for loading different file formats or providing extra capabilities.

FastScript3D is well-suited for web-based simulations of articulated robots, demonstration of robotic components, and other such applications. It includes the source code, examples, and documentation and can be customized as one's experience with Java3D increases. The only required setup is installation of Java, Java3D and the Java Plugin from Sun Microsystems.

The following FastScript3D example shows a simple web applet of three 3D cubes, with the right and left cubes rotating continuously. Both the HTML source code and java code for the embedded applet are shown. The FastScript3D commands are the capitalized text strings and are sent back and forth between the HTML page and the embedded 3D applet. Passing of strings between JavaScript and the Java Applet greatly simplifies the communication between the two different languages. The strings are constructed and programmed using JavaScript, with new string commands easily added to the language.

The model is defined beginning with the MODELCLEAR command and constructed with the MODELBUILD command. The NAME command creates a new component part and adds it into the scene under the desired parent part. The HINGE command defines an axis of rotation for the part. A simulation is then constructed that continuously applies relative rotations of the left and right cube about their defined HINGE by three degrees.

Here is easy.html

```
<!— Easiest FastScript3D Model Ever —>

<title>FastScript3D-Easy Model</title>
Easiest FastScript3D Model Ever
<P>

<!— press button to call model creation
```

```
function —>
<input type="button" value="Press here to
start applet"
 onclick="demo();">

<!— defines yout FastScript3D applet —>
<applet align=middle
  name="fs3d" code="easy.class"
  archive="fs.jar"
  width="275" height="275">
<blockquote> <hr>
```

If you were using a Java-capable browser, you would see the graphics window here.

```
</hr></ /blockquote>
</applet>

<!— uses scripting language —>
<SCRIPT LANGUAGE="JavaScript">

function model() {
  this.document.fs3d.parse("MODELCLEAR");
  this.document.fs3d.parse("NAME redbox");
  this.document.fs3d.parse("COLOR red");
  this.document.fs3d.parse("HINGE 1 0 0");
  this.document.fs3d.parse("MOVABLE");
  this.document.fs3d.parse("OFFSET -0.5 0
0");
  this.document.fs3d.parse("GEOMBOX 0.25");
  this.document.fs3d.parse("NAME
greenbox");
  this.document.fs3d.parse("COLOR green");
  this.document.fs3d.parse("GEOMBOX 0.25");
  this.document.fs3d.parse("NAME bluebox");
  this.document.fs3d.parse("HINGE 1 0 0");
  this.document.fs3d.parse("MOVABLE");
  this.document.fs3d.parse("COLOR blue");
  this.document.fs3d.parse("OFFSET 0.5 0
0");
  this.document.fs3d.parse("GEOMBOX 0.25");
  this.document.fs3d.parse("MODELBUILD");
       }
function sim() {
  this.document.fs3d.parse("SIMNAME
movethem");
  for (i=0; i<120; i++) {
   this.document.fs3d.parse("FNUM " + i + "
   RR redbox " + 3);
   this.document.fs3d.parse("FNUM " + i + "
   RR bluebox " + -3);
  }
}
function demo() {
 model();
 sim();
 this.document.fs3d.parse("PLAYAUTOON");
 this.document.fs3d.parse("PLAYRUN");
}
</SCRIPT>
```

Here is the applet easy.java
```
import java.applet.Applet;
import com.sun.j3d.utils.applet.MainFrame;
import fscore.fastscript.*;
import fscore.fastscript3d.*;
```

```
public class easy extends FS3D {
 public void init() {
  fs3dinit();
 }
 public static void main(String[] args) {
  new MainFrame(new easy(),400,400);
 }
}
```

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E-mail: Patti.Koenig@jpl.nasa.gov
http://fastscript3d.jpl.nasa.gov
For more information on the Java3D API see
http://java.sun.com/products/java-media/3D/

Manipulating deformable linear objects: programming using manipulation skills

Continued from page 3.

natural-oscillation decay times.

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Bio-inspired solutions for locomotion through the gastrointestinal tract

Continued from cover

effective biomimetic-system for adhesion and locomotion. A sort of reactive behavior, even if at low level, must be implemented to achieve bio-attachment and bio-locomotion. For example, the simplest inchworm system is based on clamping modules (which attach to the substrate) and elongation modules (which produce a displacement when at least one clamping module is active). The inchworm system is controlled by an action-perception-reaction architecture, which makes the mechanism effective. The locomotion unit has low-level control (attachment sensation) that allows activation of the propulsion system only if clamping is effective. Similar architectures drive the behavior of the arms of the octopus when it clamps to stones using its suckers.

Starting from the analysis of methods exploited by living creatures to adhere onto different kinds of tissue, we have identified in the *Taenia Solium* (tapeworm) an effective mechanism to grasp the intestine wall safely and firmly. The tapeworm head (Figure 2a) consists of four lateral suckers and a top-hooked membrane that can protrude reversibly to grasp the intestinal tissue. This solution is very effective: the tapeworm can stay attached in the intestine of its host for many months without damaging tissue or affecting the intestinal peristalsis. Suction is used to approach the tissue, but the real grasping function is performed mechanically.

We designed an artificial device that works in a similar way, and were able to mimic the adhesion mechanism of the tapeworm. The system includes a sucker and many micro-hooks integrated onto an elastic membrane. When the bottom frame moves down, a slight vacuum is generated at the sucker surface and the stretching of the elastic membrane makes the hooks protrude (Figure 2b). In this solution, the same actuation produces a volumetric vacuum and generates the protrusion of the hooks; a feature that could be very useful in terms of integration, low-power operation, and miniaturization.

Our recent work has been devoted to the microfabrication of a hooked membrane. Preliminary hooks have been fabricated in Nylon by melting them one by one according to a previously simulated process to obtain the right hook size (Figure 3). Similar hooks have been fabricated in a batch process by using electro-discharge machining and resin molding.

Two parallel approaches have been followed in order to actuate an elastic membrane that will integrate the micro-hooks in a more advanced version of the device: the first consists of exploiting the phase change of a biphasic gas (diethyl ether) trapped below an elastic membrane. The second exploits smart actuators (ionic polymermetal composites) to produce a low-voltage, actuated, bio-mimetic piston that pushes a membrane (Figure 3c).

By extending these preliminary results, we could build an active, hooked membrane made of some smart polymer that is sensitive to some external signals related, for example, to the proximity of the target substrate. If the amplified response of this signal is to protrude, the structure would be merging the sensing and the actuation functions. As such it would constitute a cellular module, able to perform reflex actions.

As a result, highly integrated bio-mechatronic locomotion systems could exhibit reflexive behaviors in addition to pre-planned actions, thus opening extraordinary new frontiers for endoscopy in the human body.

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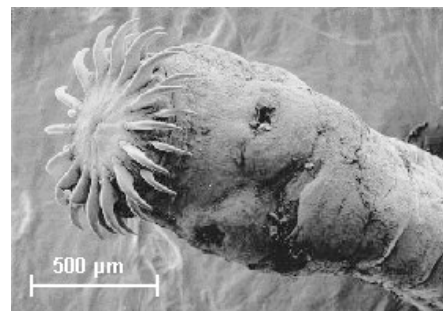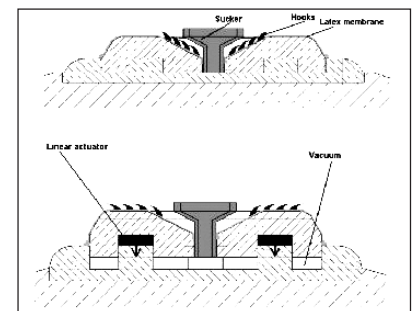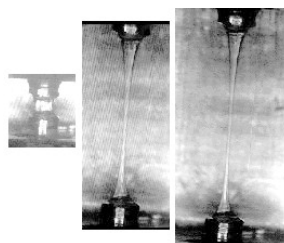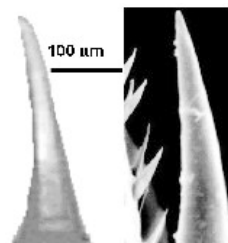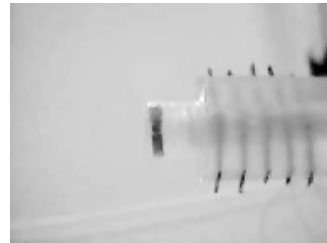

(a)   **(b)**

Figure 2. (a) Head of a tapeworm with suckers and hooks. (b) Artificial system that can generate a vacuum and simultaneously make hooks protrude.

(a)   **(b)**   **(c)**

Figure 3. (a) Three process steps for micro-hook fabrication. (b) Comparison between an artificial hook and a tapeworm hook. (c) Prototype of the IPMC actuator at maximum positive stroke and minimum negative stroke.

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Development of self-reconfiguring manufacturing control systems

Continued from page 4.

are produced by the plant, it has been necessary to design self-reconfiguring control functions for each unit of the cell so that the different pieces are locally recognised, and the corresponding work operations are executed by the unit. Self-reconfiguring control functions have also been introduced to deal with possible failures: e.g. machine M3 starts to work when a failure event occurs on machine M2 or M4.

Once the functional model has been defined by means of the IEC 61499 standard, it is tested through suitable simulation-based methods before final implementation on the target system: thus improving the reliability of the control software and reducing the overall development times and efforts significantly. Finally, the control software is generated starting from the IEC 61499 model.

Conclusions

The use of the methodology and models discussed here facilitates clear documentation and easy maintenance of the designed control solutions, improves reusability, enhances fast integration of new features, and allows for easy reconfiguration of the designed control system.[1] Future work will include the study of formal methods for the design of self-reconfiguring control functions, the definition of formal

analysis and simulation techniques for the adopted reference models, and the application of the framework to different manufacturing plants.

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Gatlinburg, Tennessee USA
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Towards haptic interfaces

Continued from page 5.

high-frequency (distributed) tactile feedback. Current investigations are towards introducing actuated redundant joints to reduce the size of the haptic display while simultaneously increasing the workspace and improving both dynamic properties and force-feedback characteristics.

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Software architecture for internet mobile robotics

Continued from page 7.

been tested from different sites. The resulting study shows that the latency and the throughput of the internet are both highly unpredictable and inevitable. Also, the response time—as shown in Table 1—is noticeable to users. It is acceptable for educational applications, however.

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Investigation of bipedal walking for autonomous service robots

Continued from page 12.

thus there is no need for any external memory devices.

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Investigation of bipedal walking for autonomous service robots

Bipedal locomotion seems to be promising for service robots in human environments that include obstacles like stairs. To investigate the stabilization and other technical requirements of bipedal robots, the Institute of Automatic Control (IRT, University of Hannover) has developed BARt-UH (Bipedal Autonomous Robot-Universität Hannover), see Figure 1. Though the motion of BARt-UH is restricted to the sagittal plane, it has proven to be sufficient for many applications of bipedal service robots. Publications relating to the results described in this paper can be found at our web site (URL on page 11).

Description of BARt-UH

Each leg of BARt-UH is composed of a hip, knee, and ankle joint resulting in six active degrees of freedom (DOF) for the robot. The motion of BARt-UH is restricted to the sagittal plane, where overlapping feet prevent falling to the side. The power supply, the power electronics, and a micro-controller board with a Motorola MPC555 processor reside on the top of the robot. Another board, this time with a Motorola MPC509 processor, is used for image capture and for the processing of a stereo vision module designed to detect stairs and their dimensions. On both micro controllers we use our real-time multi-tasking operating system called RTOS-UH (Real-Time Operating System - University of Hannover). RTOS-UH is an industrial product developed by the institute and particularly geared towards the requirements of automatic control. Sensors at the feet measure the foot reaction forces and the so-called Zero Moment Point (ZMP).[1]

For robots without an upper body—like BARt-UH—leg trajectories are responsible for overall stability. For robots operating in the sagittal plane, the Inverted Pendulum Method (IPM) introduced by Kajita & Tani plays a major role.[2] The IPM assumes a concentrated mass at the torso and neglects all other masses, including the legs. We developed new path-planning algorithms, which also consider the
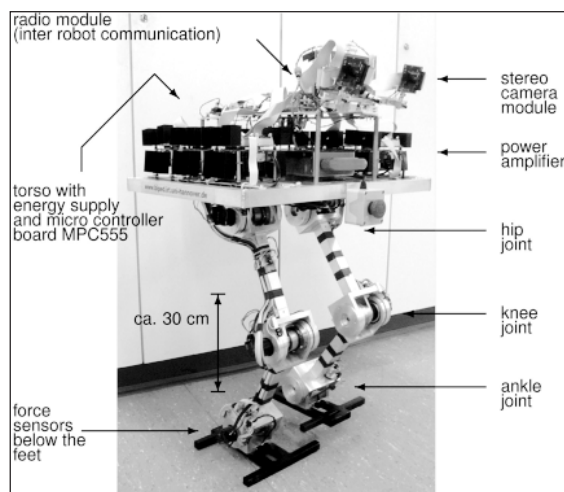

Figure 1. The bipedal robot BARt-UH.

dynamic effect of the leg as it swings. Here, one mass models the torso, and an arbitrary number of masses is used to model the swinging leg.

The method described leads to a higher gait stability with respect to the ZMP. Its great advantage is its ability to yield closed analytic solutions for the torso and the foot motion of the swinging leg, subject to only a few step parameters like step length or step duration. Therefore, intelligent and reactive behavior can be realized by tuning these parameters. Discrete-time, non-linear, observer-based, state controllers take care of the precise realization of the desired trajectories.

In cooperation with the Institute of Automatic Control Engineering (LSR) of the Technical University of Munich, a series of joint experiments were conducted and reactive, vision-guided walking realized. The research at the LSR focusses on camera-based trajectory planning for bipedal robots.[3] BARt-UH's ability to walk with easily adjustable trajectories was used in these experiments.

Figure 2. A leg of the new robot, called LISA.

3D-robot LISA

To extend the field of possible movements, a new robot called LISA (Legged Intelligent Service Agent) is under construction. It has six DOF per leg, a six component force-torque-sensor integrated in the foot, and a balancing sensor on the torso. Figure 2 shows the already-finished leg with one DOF in the knee joint and two in the ankle joint. The hip joint, with three DOF, is currently under construction. Bending beams with attached strain gages integrated in the foot allow the measurement of ground reaction forces. Additional toe joints (passive DOF) enable the robot to perform a "rolling" foot motion.

An artificial balancing sensor that measures the six DOF of translation and rotation for improving stability is also in development. A Motorola MPC555 is used in this sensor for intelligent data processing. To this end, the kernel of the operating system, RTOS-UH, has been modified to work as a system-on-the-chip:

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