VIRTUAL PROTOTYPING AND MULTI-MODAL INTERFACES TO TEST THE CONTROL OF AN ORTHOSIS

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ABSTRACT

The test of wearable robots with users can be dangerous, especially initially, when the control algorithms and the controller are tested. The use of virtual prototypes, as opposed to creating real ones, whilst not eliminating the need to manufacture an ultimate prototype for the final tests, eliminates intermediate tests which could potentially be dangerous for a user. Multi-modal interaction and virtual prototyping are used to test and evaluate the controllers. The Ikerlan research centre has designed a 2 DoF arm orthosis to research the issue of the interaction of such devices with the environment. This orthosis was not physically constructed, but a virtual prototype was created for testing the performance of the different control algorithms implemented.. The multi-modal interfaces considered are composed of traditional devices, one haptic device (*Phantom*) and a video-based motion capture and mark recognition system. As a result, two test platforms have been developed, where the orthosis is tested in Real-Time simulation based on the real movements of the user. Augmented Reality (AR), Virtual Reality (VR) and video-based optical motion capture techniques are used in order to evaluate a prototype.

INTRODUCTION

An exoskeleton or "human amplifier" is a mechatronic system worn by a person which offers the user the possibility of enhancing their physical skills. The term IAD (Intelligent Assist Device) is used for a special kind of human amplifier, a biomechatronic device, the purpose of which is to help the user perform a daily activity which requires a certain amount of effort. The word orthosis can be used in the same context. Ikerlan has designed and constructed an upper limb IAD of 5 DoF (Degrees of Freedom) (Martinez et al. 2007), an exoskeleton designed to help the user perform a routine activity requiring effort in the workplace.

As a preliminary step, and above all to research the issue of the interaction of such devices with the environment, a 2 DoF arm orthosis was designed. This orthosis was not physically constructed, but a virtual prototype was created for testing the performance of the different control algorithms designed. For this purpose multi-modal interaction techniques were used after integrating them with the Virtual Prototype. These multi-modal interfaces combine classic interaction devices (the mouse and the keyboard) and haptic interfaces (*Phantom*), as well as a video-based motion capture and mark recognition system. As a result, the orthosis is tested in Real-Time simulation based on the real movements of the user.

An active orthosis can be considered as a manipulator which connects directly with the human user and his position and force control should be considered. Normally, the user creates the movement set-point values, after detecting his "intention" and closes the loop helped by the sensors the human body posses. There are however applications, in rehabilitation for instance, where the set-point values may be generated in a different way. In principal it is not possible to control the position and force simultaneously, although strategies have been developed to allow the position and the force to be modulated.

A classic in this field is the Hybrid Controller strategy put forward by Raiber and Craig (1981). The controller carries out its action using selection matrixes which establish some spatial directions where position control must be carried out and some others where force must be controlled. In this way the force and position control actions are uncoupled by using the appropriate treatment of the spatial geometry where the manipulation task is being carried out. Different variations appeared later, which did require knowledge about the restrictions of the environment. Another classic strategy is Impedance Control (Hogan 1985), which does not control the position or the force but the dynamic relation between the two. The concept of Impedance control is based on the assumption that during all manipulation tasks the environment contains kinetic inertias and restrictions, i.e. systems which accept force as input and respond through displacements. This type of system is known as *admittances.* In turn, the manipulator in contact with the environment must adopt the behaviour of an *impedance*, i.e. a system which responds to a displacement by exercising a certain force on the environment. If the manipulator presents an inescapable inertial element, the representation of the system can always be modified to include this element in the environment modelling. This type of control strategy is deemed to be very suitable for IADs, although it needs to be adapted depending on the specific application.

The use of virtual prototypes, as opposed to creating real ones, whilst not eliminating the need to manufacture an ultimate prototype for the final tests, eliminates intermediate tests with real prototypes which could potentially be dangerous for a user. With the goal of getting a more realistic use of the virtual prototype, multi-modal interaction will be used. In this interaction, different input channels have been used (not only traditional devices mouse and keyboard). On one side the haptic interfaces such as *Phantom*, supply a force feedback, thus facilitating interaction testing with virtual environments. But other techniques based on motion capture enable real user movements to be used as an input for the virtual world.

Motion capture can be considered as the computer's sense of sight, through which it is able to observe the movements carried out by the user. Whilst this is a fairly new technology, a large number of approaches have been developed in order to create the capture process, using various technologies: acoustic, electro-magnetic, mechanical... But currently those most commonly used are optical capture systems for three main reasons: accuracy, speed, and freedom of movement for the user. Within this group two sub-types can be considered: infrared optics and video-based optics. Infrared optics is more accurate but requires rather expensive special hardware (infrared cameras). Video-based optics works very similar to the sense of human sight, where based on the image, an attempt is made to capture the position and movements of the object under observation. The work carried out and presented in this paper aimed to create an environment to evaluate the correct performance of a virtual prototype of the orthosis, but on a real user. This is possible by applying a new interaction paradigm: Augmented Reality (AR) (Azuma 1998). The difference between Virtual Reality (VR) and AR (Lores and Gimeno 2007) lies in the way they treat the real world. VR immerses the user into a world which completely replaces the real world, whilst with AR the user interacts with a mixture of the real world and virtual information.

This paper describes, firstly, the orthosis designed, as well as its modelling on *Dymola/Modelica*. Continuing with, the description of the position/force algorithms implemented and some results obtained in simulation are presented. Then, the multi-modal interfaces used, *Phantom* haptic device and AR paradigm, are stated, as well as the virtual prototype and the test platforms carried out based on them. Finally, the test procedures for the orthosis are explained.

ORTHOSIS DESCRIPTION AND MODELLING

Orthosis description

In order to make an initial approach towards the final objective, the IAD or orthosis of 5 DoF (Martinez et al. 2007), it was decided to simplify the system by reducing it to two DoF. An orthosis was therefore designed with three

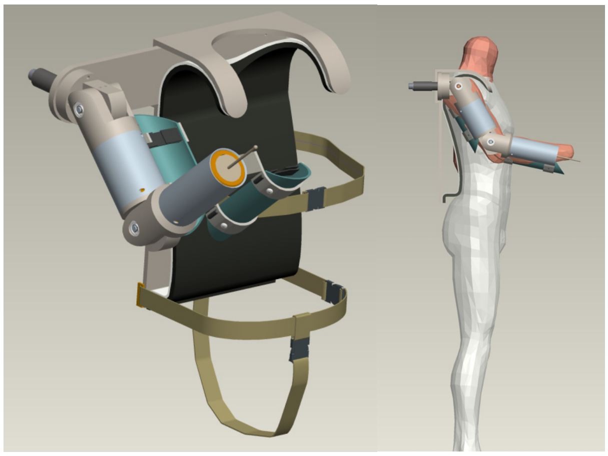

Figure 1: Virtual prototype of the 2 DoF orthosis

main parts: the two which will move jointly with the arm and forearm and a third fixed to the body. In order to achieve the two DoF of the moveable parts, two rotating joints were used: one for the shoulder and another for the elbow. As a result, the movement of the arm is limited to a vertical plane. The third main component is a kind of backpack which will be secured to the user's back, as shown in Figure 1, and will withstand all the efforts made by the orthosis.

The main function of the exoskeleton, in so far as it has been designed as a support device, lies in amplifying the torque with respect to the elbow joint exercised by the human muscles when handling loads. In order to guarantee this functionality, the device consists of two DC motors to motorise the two joints with which it is equipped. Graphite brush motors by Maxon were chosen. More specifically, the *RE 36 ∅36* model, which is capable of supplying power of up to 70 watts when operating axially. Each drive is fitted with a gearhead and a tachogenerator also by Maxon: *GP 32C ∅32 1-6 Nm* gear with 190:1 reduction, and *DC Tacho ∅22 mm* and 0.52 V tachogenerator. A servoamplifier, *Maxon ADS 50/5* is used for current and speed control.

The abovementioned drives are placed near the rotating axes, hidden inside the cylindrical pieces as shown in Figure 1. The forearm part of the orthosis weighs 1.94 kg, and its moment of inertia with respect to the rotating axis is 261 $kg{\cdot}cm^2$. The arm part weighs 3.5 kg and has a moment of inertia with respect to the rotating axis of 820 $kg{\cdot}cm^2$.

Given that this first orthosis design was created to research the interaction with the environment, a force sensor was fitted to the designed orthosis at the tip of the forearm cylinder, at the level of the user's hand. This sensor was designed by Ikerlan for robotic manipulators and supplies the force exerted at the tip in the 3 spatial coordinates.

Modelling of the orthosis

Although the design described has not been physically constructed, it has been created virtually. In other words, a virtual prototype has been developed consisting of the

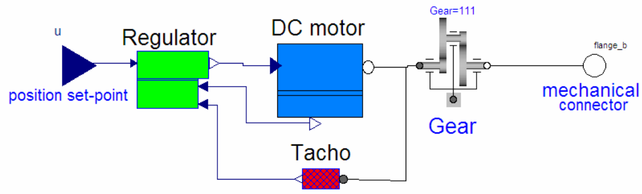

Figure 2: Axis model in *Dymola*

dynamic model of the exoskeleton and upper human extremity, and of the controller which deals with the positioning of the hand in the work plane and the force exerted by the orthosis against the environment in the event of collision.

The dynamic part of the model was developed in the *Dymola* modelling and simulating environment, which bases its operation on the *Modelica* modelling language. Both elements from commercially available model libraries as well as objects specifically designed for this application have been used in the composition of the model.

The model has been designed considering two parts. On one side are the axes commanded by the actuators and on the other side the three/dimensional mechanical components. As has been mentioned in the previous point the drives selected are identical for both degrees of freedom of the system. Therefore the modelling of the two axes are the same.

Figure 2 shows the model of an axis which comprises a DC motor, a gear, a regulator and a tachogenerator to measure the rotation speed. Figure 3 shows the typical model of a DC motor. It consists of the electrical part and the mechanical part. The mechanical part is finished off by the component for motor load modelling. This subsystem has the working voltage of the motor as an input while its output port informs about the current value on the circuit. Although the two typical control loops (an internal current one and an external speed one) have been modelled on the regulator, when the impedance control is applied only the current loop is used, given that the control law generates the torque set-point values for the actuators.

Figure 4 shows the complete dynamic model, where the subsystem of the axes previously described has been included twice to control the angular position of each DoF. The model brings together the parts from the top half of the human body starting from the trunk, and moving onto the neck, head and the shoulders from where the upper limbs hang. For modelling the different parts of the body three-dimension components from the *Dymola* mechanical library, in the shape of spheres and cylinders, have been taken into consideration, where the inertia values and masses have been fixed in accordance with some average values. In the case of the right limb, the mass and inertial values correspond to the human arm in addition to the orthosis components. The mechanical model is completely rigid with the exception of the shoulder and elbow articulations, which have been reduced to one DoF each. The articulations have been modelled using rotary joints

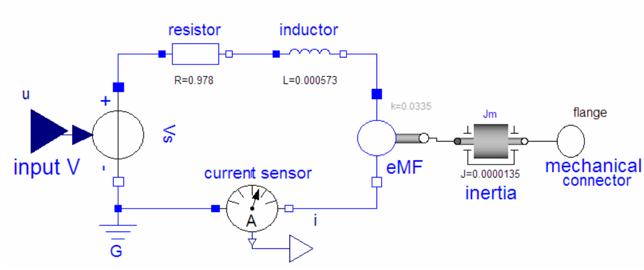

Figure 3: DC motor model in *Dymola*

included in the mechanical library, although only the joints corresponding to the right limbs are actuated and controlled by the motors.

In order to carry out robustness tests with the implemented controllers, an external force has been added to the right hand whose value depends on the weight of the load fixed during each test.

Finally the model includes an additional three-dimensional component which serves to implement a vertical wall placed at a configurable position. The interaction force between the orthosis and the wall has been modelled in *Modelica* language within the “collision” element. The triangular icons correspond to the input and output interfaces of the model. These interfaces serve as a connection between the different controllers implemented using *Matlab/Simulink* blocks and the model described in *Dymola/Modelica* and exported to *Simulink* as an S-function.

POSITION/FORCE CONTROL ALGORITHMS

The basic control of an orthosis type device is based on position control, where the user creates the motion set-point value and closes the loop with the help of the sensors possessed by the human body. A key element is the detection of the “intention” of the user for creating the motion set-point values from it. This characteristic, of great interest to researchers, is a fundamental difference between an orthosis and robotic manipulators. Another very important factor to consider is the interaction with the environment, especially from the point of view of controlling the force exerted in order not to harm people

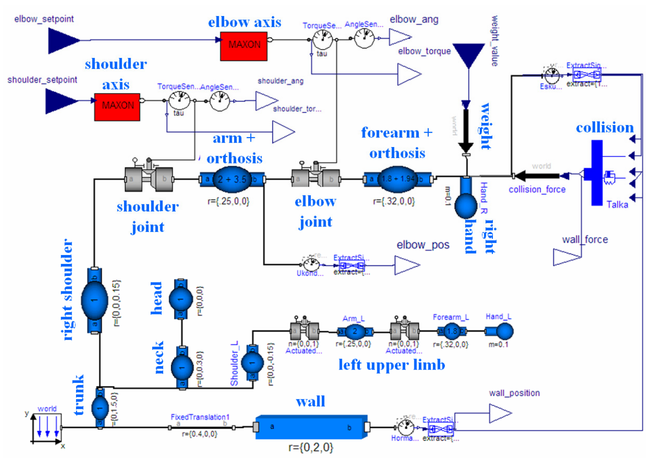

Figure 4: Complete dynamic model of the orthesis designed

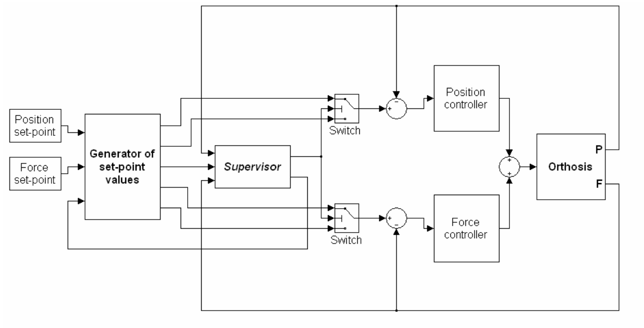

Figure 5: Diagram of hybrid position/force control

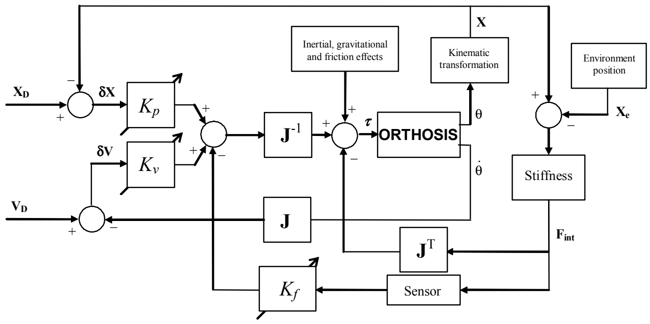

Figure 6: Structure of the impedance control of the orthosis

who may be present in the field of action of the robotic device. In robotic manipulators there are two classic types of position/force control: hybrid control and impedance (or admittance) control. It has been considered that these types are valid in the case of an arm orthosis, although they have particular characteristics, different from the case of robotic manipulators.

Hybrid control

A hybrid position/force controller has been implemented in the orthosis, following the diagram shown in Figure 5. It basically consists of two independent controls, one for position and one for force, and a supervisor, which depending on the contact with the environment, switches between one type of control and the other. The supervision is based on the information supplied by a force sensor in the orthosis, in this case at the end of the arm. In a more general case, a system distributed with force sensors throughout the body/casing of the orthosis might be considered.

The supervisor, in addition to the set-point generator, is responsible for making the transition between controllers "smoothly", to avoid bouncing and to ensure the stability of the system. In the case of the orthosis being described, for each one of the axes the control position is a proportional control and the force control is a Pl control. The switching between position and force control is not carried out in a simultaneous fashion on the two axes, but when moving with interaction, and depending on the relative position with respect to the contact surface, one of the axes carries out the position control and the other the force control. With this system the position of the orthosis can be controlled very accurately as well as the force exerted on the environment.

Impedance control

Another classic system, and very interesting in the case of an orthosis, is impedance control. Impedance control does not need a supervisor and is capable of taking control of a compound task, with phases of free and restricted motion, maintaining the stability of the system without changing the control algorithm. It is based on the idea of controlling the dynamic relationship between the force and position variables of the physical system. It assumes that in every manipulation task the environment contains inertia and cinematic restrictions, i.e., systems that accept forces as input and respond through displacements (admittances). In turn, the manipulator in contact with the environment must adopt the behaviour of impedance and responds with a certain force to the displacement of the environment. The general strategy can be established in terms of controlling a motion variable and, in turn, equipping the manipulator with a response to disturbances in the form of impedance.

In impedance control, the functional form of the torque of the actuators of a manipulator is well known:

$$\begin{aligned}\tau_{\mathbf{act}} &= I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}K\left[\mathbf{X_0}-L(\theta)\right]+S(\theta)\\ &+I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}B\left[\mathbf{V_0}-\mathrm{J}^{-1}(\theta)\omega\right]+V(\omega)\\ &+I(\theta)\mathbf{J}^{-1}(\theta)M^{-1}\mathbf{F_{int}}-\mathbf{J}^{\mathrm{t}}(\theta)\mathbf{F_{int}}\\ &+I(\theta)\mathbf{J}^{-1}(\theta)G(\theta,\omega)+C(\theta,\omega)\end{aligned} \tag{1}$$

where each line of the second member represents a contribution to the total torque of a different nature: the first line corresponds to terms dependent on the position, the second to terms of speed, the third to terms of force and the fourth to terms of inertial coupling. This equation expresses, in the field of the actuators, the behaviour that the controller must be capable of inducing in the manipulator, in the form of non-linear impedance. The input variables are the desired Cartesian positions and speeds, and the terms, linear or non-linear, which specify the required dynamic behaviour, characterised by the magnitudes M, B and K. Figure 6 shows the typical structure of impedance control, where the feedback gains of the position, speed and force loops, K_p, K_v and K_f respectively, depend on the inertia and reference mass tensors, and on the stiffness K and damping B (design parameters), and are deduced from the control law (1).

The F_{int} force feedback has the effect of changing the inertia apparent in the manipulator. But an interesting characteristic of the impedance control system is that it can be applied without having a force sensor. In this case the force is not explicitly controlled, but depending on the impedance values used in the design of the controller, the force exerted by the system on the environment is limited.

As mentioned previously, these position/force control systems have certain special characteristics when there is a user wearing the orthosis and modulating the resulting behaviour in the interaction with the environment. The

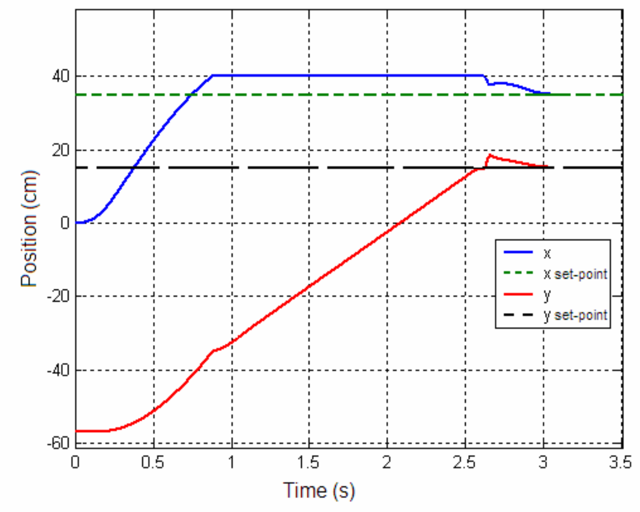

Figure 7: Position control with hybrid algorithm

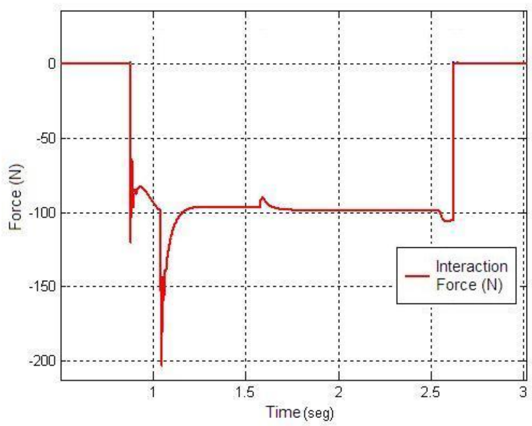

Figure 8: Force interaction with hybrid control algorithm

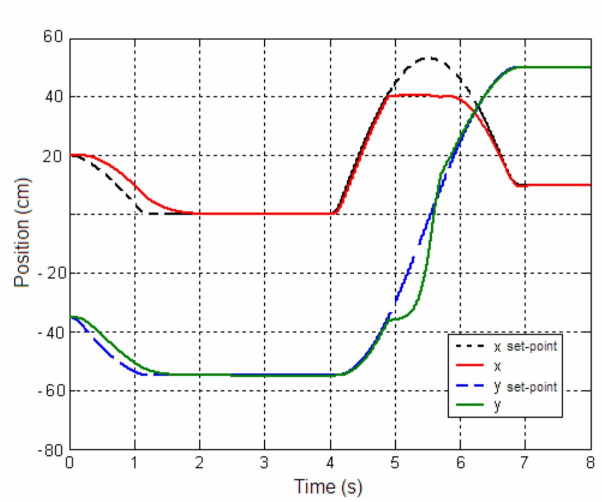

Figure 9: Position control with impedance algorithm

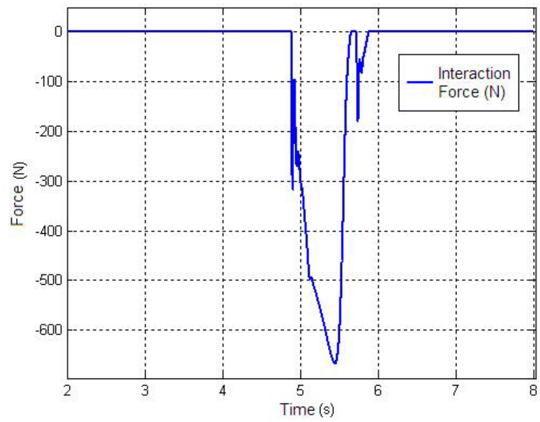

Figure 10: Force interaction with impedance control

different techniques applied in this research (motion capture system, VR, AR, etc.) help to evaluate the behaviour and to optimise these control systems in the case of an orthosis.

Simulation results

To test the capability of the implemented position/force controllers different tests were carried out in simulation, varying parameters such as the hand trajectory or the situation of the wall. It was considered a reference system, which was situated on the shoulder axis so that the YZ plane remains parallel to the simulated vertical plane, while the XZ plane remains parallel to the floor.

Figure 7 shows the evolution of the coordinates of the tip of the orthosis with the hybrid control algorithm when moving from the lowest possible point, (0, -57) cm, to a higher point, (35, 15) cm. In this case the desired trajectory penetrates into the wall located at 40 cm on the X axis. Figure 8 shows the force exerted by the orthosis when interacting with the wall during the movement with the force set-point value fixed at 100 N. The first significant perturbation appearing both on the position and force graph corresponds to the moment of impact with the wall. After the initial impact, the force exerted presents an even greater perturbation due to the force controller switching, so that the shoulder articulation goes on to be force controlled and the elbow, position controlled. The third discontinuity and the least significant for the force is due precisely to the contrary switching, with the elbow articulation being force controlled and the shoulder position controlled. Finally, there is a small jump in the position before the final set-point values are reached which corresponds to the moment of separation from the wall. From this moment on both articulations are position controlled until the movement finishes.

As has been mentioned in the previous point, the impedance control philosophy is completely different given that the aim is not to explicitly control the force nor the system position, but the dynamic interaction between the system and its environment. As Figure 9 shows the evolution of the position coordinates of the tip of the orthosis together with its set-point values. In a first stage the tip is driven to the lowest position (0, -57) cm. After a couple of seconds a new trajectory is generated with the aim of positioning the arm in the point (10, 50) cm. The tracking error is minimum until the impact with the walls situated at 40 cm on axis X occurs. At this moment the position error increases coinciding with the increase in the interaction force graphically shown on Figure 10. Noteworthy is the fact that the results shown correspond to a simulation obtained with a controller implemented without force feedback. Supposing that a force sensor is available, the interaction force is explicitly controlled.

MULTI-MODAL INTERFACES AND AR

Multi-modal interfaces are those where more than one interaction channel is used with the computer. This research uses traditional devices such as interaction channels (keyboard and mouse), a haptic device (*Phantom*) and motion capture based on video (ARToolKit 2008).

An interaction paradigm is an abstraction of all the possible interaction models organised in groups with similar characteristics. There are at present 4 paradigms: the desktop computer, virtual reality (VR), ubiquitous computing and augmented reality (AR). The main difference between AR with respect to VR lies in the way they treat the real world. The VR systems aims to submerge the user in the virtual world, while the AR let the user see the real world around them and increase this vision adding virtual information, therefore, it brings virtual information to the real world.

In the case under study, both VR and AR techniques have been used in two different test platforms. The AR enables information to be taken from the virtual prototype to the real world and interaction in this virtual world or with virtual options. This is done using user movement as a data source for the movement of the orthosis virtual prototype, and by visualising the performance of the orthosis on the real user, adding a 3D model of the prototype to the video captured of the user in real time (non-immersive AR).

Phantom haptic interface

The *Phantom* is a haptic joystick made by the North American firm SensAble Technologies. More precisely, the *Phantom* is a product line of haptic devices makes it possible for users to touch and manipulate virtual objects. In the case of this research the *Phantom Desktop* device was used. It provides precision positioning input with 6 DoF positional sensing and high fidelity force-feedback output. Portable design and simple parallel port interface ensure quick installation and ease-of-use.

On the other hand, SensAble offers the *OpenHaptics* software toolkit. This toolkit enables to add haptics and 3D navigation to specific simulation and visualization applications. The *OpenHaptics* is patterned after the *OpenGL API*, making it familiar to graphics programmers. Using the *OpenHaptics* toolkit, it is possible to leverage existing *OpenGL* code for specifying geometry, and supplement it with *OpenHaptics* commands to simulate haptic material properties such as friction and stiffness.

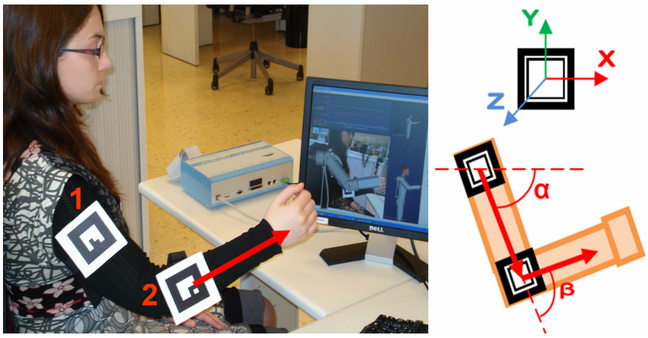

Figure 11: Marks and angle calculation

The *OpenHaptics* toolkit includes the *Haptic Device API* (HDAPI), the *Haptic Library* (HLAPI), utilities, *PHANTOM Device Drivers* (PDD), and source code examples from which start developing new applications.

Video based motion capture and AR techniques

Video based motion capture consists of applying computer vision techniques, in order to recognise and obtain both the position and the orientation of the objects or people reflected in the images. This problem, which may at first seem simple, is very costly computer-wise and in certain cases remains unsolvable. In order to help resolve it, marks are often used, which tend to be flat with a specific shape (square, circular, etc.) with an image printed on them (Figure 11). With these markers, both the shape and the image are known in advance, thus enabling the vision problem to be assessed on recognising these marks, and not any object or person, obtaining a much simpler process of recognition and calculation (position and orientation). This type of capture system is perfect for use in AR systems, as it minimizes the problem of coherence (registration) between the virtual information and the observed images.

The main advantage of these kinds of capture systems is the user's freedom of movement, as he does not have to wear wired sensors, but simply some small cards with the markers printed on them. However, these kinds of systems also have significant optical type disadvantages, being their main problem the concealment of the markers. If the user covers the markers with his movements, the capture system cannot see them. This problem is partially solved by calculating the possible position and orientation of the hidden marker by using its previous data and assuming that it will follow a similar trajectory. One commonly-used technique in this respect is the implementation of Kalman filters.

VIRTUAL PROTOTYPE AND TEST PLATFORMS

Based on the dynamic model and the controllers presented in previous sections, a Virtual Prototype has been developed consisting of the dynamic model of the exoskeleton and upper human extremity, and of the controller which manages the positioning of the hand in the work plane and the force exerted by the orthosis against the

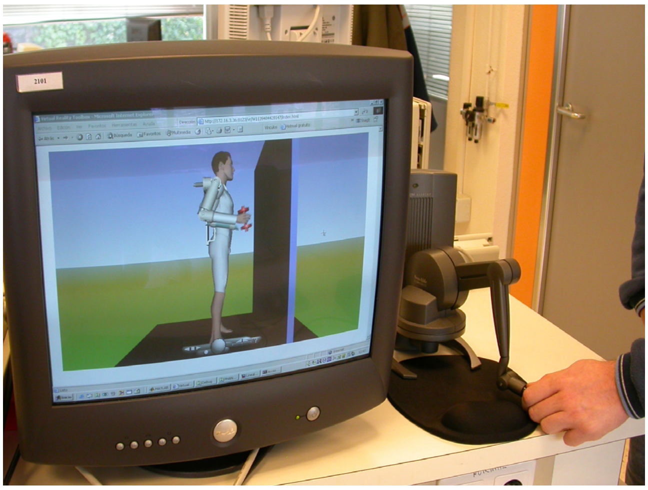

Figure 12: Virtual Prototype and *Phantom* haptic device

environment in the event of collision. The prototype is completed with the integration of multi-modal interfaces.

A *Simulink* model comprising the controller and the physical part imported from *Dymola/Modelica* was modified to obtain a model suitable for execution in real-time. Some functions were added for the communications via UDP with the multi-modal interfaces.

Based on the aforementioned *Simulink* system, and using the *RTW* tool from MathWorks, an executable application was obtained which was downloaded onto an *xPCTarget* compatible PC/104 platform. The simulation is carried out with a fixed step integration algorithm of 1 ms, and communicates with the different multi-modals interfaces whose functions are, first, generate the position set-point values for the tip of the orthosis and, second, guarantee a sensorial feedback between the user and the prototype.

Using diverse aspects of the multi-modal interfaces two different platforms were implemented with the aim of validate all control features. The first one is based on a haptic interface and a virtual 3D representation of the orthosis and the environment. The second system uses motion capture and AR techniques in order to generate the position trajectory and visualize the resultant movement.

***Phantom* haptic interface based test platform**

As has been mentioned before, the *Phantom* is a haptic device which boasts a total of six degrees of freedom, as well as force feedback. With the help of the *OpenHaptics* toolkit only two of the Cartesian directions and their corresponding movements are integrated into the virtual prototype of the orthosis as its movement is restricted to one plane. The *Phantom* takes charge of defining the position set-point values on each movement, allowing the user to control the arm movement at all times. On the other hand the force feedback enables the sensation of colliding with the virtual environment or that of supporting a weight at the hand. However the position set-point values generated with this device are not those natural to a human hand.

The system is completed with a graphical model that includes the orthosis, a human body and a vertical wall. Several two dimensional plots are also added to inform about the temporal evolution of the most significant variables. The link between the virtual world and the real-time simulation is established using the *Matlab*'s tool named *Virtual Reality* toolbox. In this way, every mobile part of the virtual scene shows a position and an orientation according to the data incoming from the dynamic simulation. Figure 12 shows an example of handling on the Virtual Prototype.

Motion capture based AR test platform

The movement capture used is the video based optical type. To this effect, *ARToolKit* (2008) meets the requirements stipulated for this study. *ARToolKit* works by detecting and capturing both the position and the orientation of flat square markers (Figure 11). These markers always adopt the form of a black square, on a white background, with an identifying image inside. Two markers are placed on the user's arm to capture the information from it.

For the visualisation offers 3D drawing capacity, but they are very basic, simply enabling the designer to draw by using *OpenGL* (a low level graphics library) or *VRML* (a high level graphics library). It has therefore been considered that the *OpenSceneGraph* (OSG 2008) high level drawing library offers greater capacity, mainly due to the fact that it is based on the use of a scene graph. Consequently, the visualisation part has been developed by using this library. Although *OSG* has no software for AR applications, there are some approaches, such as the *OSGART* library, which combine the *ARToolKit*'s AR capacity with the visualisation power of *OSG*. In the case in question, a new *OSG* node has been created, *JesAROSGTexture*, which is responsible for showing the images captured by *ARToolKit* in a texture. This node is simply included in the *OSG* scene graph and is always painted in the background of the application. Finally, to make the virtual information (orthosis model) coincide with the real image (user), the *OSG* camera is configured so that it coincides with the camera values captured by *ARToolKit*. In this way, the problem of "registration" between the virtual information and the real information is reduced, as the system is ultimately drawing on the same image from which the calculations have been obtained.

TEST PROCEDURES AND RESULTS

Both described approaches are perfectly valid for testing both the position control and the force control ones. In any case, the system fitted with the *Phantom* has been applied mainly for the start up of the controller part related to the interaction with the environment. As can be seen in Figure 13, the behaviour of the orthosis with the position/force algorithms can be seen on different graphs, obtaining similar results to those shown in Figures 7, 8, 9 and 10.

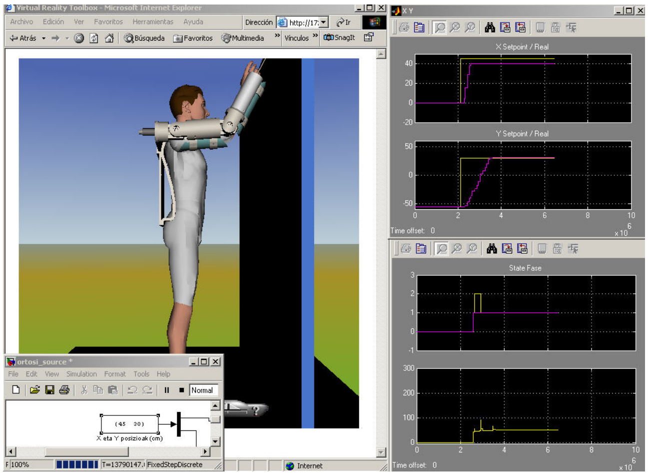

Figure 13: Test procedure with Virtual Prototype and *Phantom* haptic device

From the moment of the impact the user can perceive on their hand the interaction force regulated by the controller.

For testing the AR system, a *MFC* based application on *Windows* platform has been developed, in which 5 views have been included using *OSG*, as well as some view configuration dialogues. Figure 14 shows the typical screen. In the first of the views, the view of the virtual prototype on the real user in the virtual environment (with or without wall) is shown, following the movements calculated by the control system. In the two right-hand views a virtual human is shown with the orthosis in one of these moving in accordance with the set-point values generated by the capture system, and in the second with the values calculated by the control and dynamic simulation subsystem, according to the interaction environment and the chosen position/force control algorithm. These two views enable the user to visually compare the performance of the control, as with this interface the feedback from the force exerted is replaced by the visual feedback. Finally, in the fourth and fifth views, graphs of the positions and of the force exerted in the case of interaction with the virtual wall are shown.

CONCLUSIONS

The virtual prototyping is a great help when testing new control systems related to safety and comfort. In the case of an orthosis or a wearable robot, the first controller test trials can be dangerous for the user as they are carried out on a real prototype. The integration of multimodal interaction and virtual prototyping, such as haptic devices and AR systems based on motion capture, enable testing of the controllers to be carried out in more natural conditions, similar to those of the user themselves interacting with the real system.

To investigate the interaction control techniques of an arm orthosis with the environment and as a simplified case, a two DoF orthosis has been designed, where classic position/force control strategies have been implemented. The integration of some multi-modal interfaces, such as a haptic device or a motion capture based AR system, enables controllers to be tested. Two test platforms have been made and evaluated: one based on the *Virtual Reality* toolbox from MathWorks and on the *Phantom* haptic device, and a second one which combines optical motion capture based Virtual Reality and Augmented Reality. With the first one precise force feedback is obtained, and with the second one, the AR system permits the generation of the movement set-point values by a real user, in natural movements.

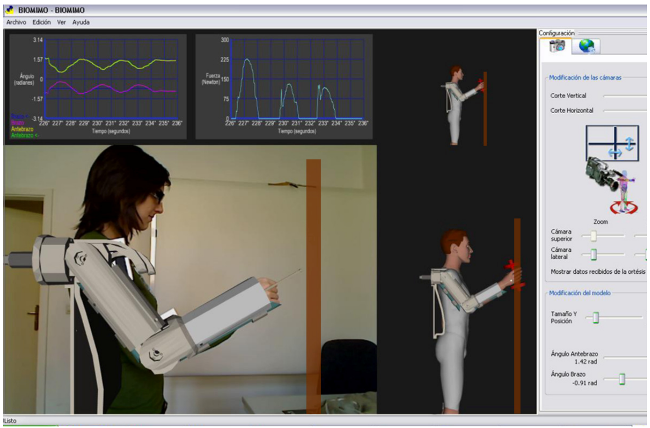

Figure 14: Test procedure with Virtual Prototype and motion capture based AR system

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REFERENCES

ARToolKit. 2008. "ARToolKit Software library for building Augmented Reality applications", available in http://www.hitl.washington.edu/artoolkit.

Azuma, R. T. 1997. "A Survey of Augmented Reality", in *Presence: Teleoperators and Virtual Environments*, August, 355–385.

Hogan, N. 1985. "Impedance Control: An Approach to Manipulation : Part I - Theory. Part II - Implementation. Part III – Applications". *Journal of Dynamic Systems, Measurement, and Control*, 107, 1-24.

Lorés, J. and J.M. Gimeno. 2007. "Metáforas, estilos y paradigmas", in *Curso Introducción a la Interacción Persona-Ordenador*, cap. 2, http://griho.udl.es/ipo/ipo/libroe.html.

Martinez, F., I. Retolaza, E. Lecue, J. Basurko and J. Landaluze. 2007. "Preliminary Design of an Upper Limb IAD (Intelligent Assist Device)", in *Challenges for Assistive Technology – AAATE07*, IOS Press, ISBN 978-1-58603-791-8.

OSG. 2008."OpenSceneGraph". Available in http://www.openscenegraph.org.

Raibert, M.H. and Craig J.J. 1981. "Hybrid Position/Force Control of Manipulators". *Trans. of the ASME*, vol. 102.