Jornadas Nacionales de Robótica
Spanish Robotics Conference
14-15 Junio 2018 http://jnr2018.eii.uva.es

Humanoid Balance Control based on Force/Torque and Visual Information

J. M. Garcia-Haro*, S. Martinez, C. Balaguer

Robotics Lab, Systems Engineering and Automation Department, Carlos III University of Madrid, Avd. Universidad, 30, Leganés, 28903 Madrid, Spain

Abstract

Different robotic systems are used into the service robot field. The most complex kind of robots dedicated for these tasks are humanoid robots. But these robots are the most versatile at the same time. This thesis presents the use of the humanoid robot TEO (Task Environment Operator) as a waiter robot. In this case, the robot will try to imitate a waiter. Therefore in this research, there are two main goals. The first one is related with the transporting task. The idea is to learn how a humanoid robot should manipulate objects without physical grasping. The most important will be maintaining the object balance with an appropriate control system to deal with this specific service application. The purpose is understood the motion's physics for the object balance through the use of sensor fusion. The second aim is related with the whole-body balance control of the robot and the effects of this control on the manipulation task. Applying different push-recovery strategies, the robot should be able to keep its stability and maintain the equilibrium of the transported object.

Keywords:
Robotic manipulators, Stability, Sensor fusion, Robot control.
Thesis Info: Object Oriented Control System based on Fusion Sensor in Humanoid Robots for Transport Tasks
PhD Student: Juan Miguel García Haro
Tutors: Santiago Martínez y Carlos Balaguer
Start/Finish Date: Nov 2015 - Nov 2018
PhD program: Electrical, Electronic and Automatic Engineering
University: Carlos III de Madrid

1. Introduction

Robotic technology is going through major revolutions. We are now closer than ever to the aim of service robots than can help people in their daily living activities. In the last two decades, service robots were successfully fielded in hospitals (Arumugam et al., 2010), museums (Burgard et al., 1999), and office buildings/department stores (Kulyukin et al., 2005), where they perform janitorial services, deliver, educate, or entertain. Robots have also been developed for guiding blind people (Lacey y Dawson-Howe, 1998). Robotic aids for the elderly have been developed, but many of these robotic aids are mechanical aids (Balaguer et al., 2006) that put the cognitive load on the patient side. There has been little research to date in terms of assisting elderly people with cognitive tasks, such as remembering medication schedules. However, human-robot interaction, autonomous systems and planning have seen major developments recently. The time is ripe to leverage the various technologies into the lives of people, where the need for personal assistance is essential to improve the quality of life.

*Corresponding Author.
Emails: jgarciah@ing.uc3m.es (J. M. Garcia-Haro), scasa@ing.uc3m.es (S. Martinez), balaguer@ing.uc3m.es (C. Balaguer)
URL: http://roboticslab.uc3m.es (J. M. Garcia-Haro)

As the expectation on humanoid robots to operate as human helpers and social companions grows, the need to improve their motor skills becomes increasingly important. Equipped with highly dexterous anthropomorphic systems, sensors for environmental awareness, and powerful computers, humanoid robots should be able to handle many basic chores that humans do. Yet they cannot, not to the level that would make them practical.

At the Carlos III University, the research group "Robotics-Lab" have started to develop an autonomous mobile humanoid robot, which should be inserted as assistance or personal robot in an office or a workshop environment as a *Waiter Robot*. The main component of such a robot for handling objects is its hand which carries a tray. The design of our hand-tray is based on the observation of the motion range of a typical human waiter.

Humanoid robots are difficult systems to model and control because of their highly dimensional and its numerous joints, and also they operate under contact and geometrical constraints. This work describes the design of a unified control methodology that simultaneously combines all required processes to achieve advanced compliant manipulation and locomotion behaviours. At the same time, this control methodology works under the physical constraints imposed by the transported object tasks.

In fact, the waiter application is a combination of different tasks, which try to simulate the behaviour of a typical human waiter. For this purpose, the humanoid robot should be able to keep balancing taking into account transported object's motion.

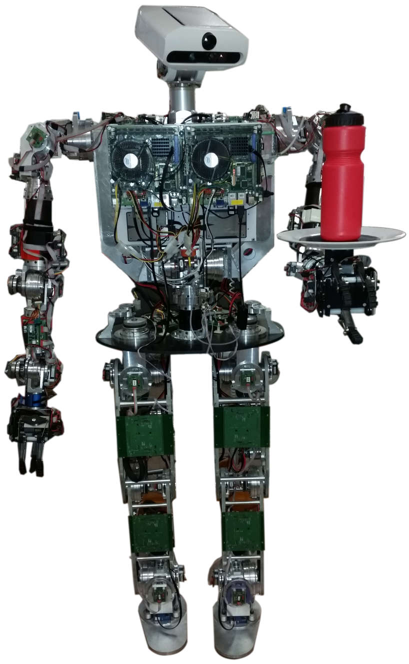


Figure 1: The whole-body humanoid robot TEO developed in the Carlos III university by the "RoboticsLab" research group, working as a waiter.

Moreover, it is important to measure the disturbances generated during the execution of a transport task. This permits to have a better control over the whole-body robot. On the other hand, the humanoid robot should be able to keep balancing of the bottle. The equilibrium of the drinks is controlled basing on an simplified model in which a camera and a force-torque sensor estimate the range of stability.

Part of the strength of this thesis should rely on a whole-body kinematic and dynamic model, which exploits the high dexterity of the humanoid mechanisms. This mathematical model must give the opportunity to create compliant and accurate skills without relying on high motion planning computations. Operating with this model enables the implementation of compliant motion behaviours related with manipulation tasks while simultaneously being able to assure the balance or the corresponding locomotion task.

Therefore, this article is organized as follows: The next subsection presents the main idea of the waiter robot application, justifying the choice of a humanoid robot for this kind of tasks. In the second and third section, it is introduced the two last published research. These works will contribute significantly to the corresponding author to achieve the objectives for this thesis with the same title as the article. The second section is related with the use of visual data and fuzzy filters to improve de accurate and control of the bottle (Hernandez-Vicen et al., 2018). And the third one presents an experimental method to eliminate dynamically errors from the force-torque sensors of the ankles Martinez et al. (2018). In the next chapter, it is explained the last works to integrate the thesis, and also some conclusions and expectation for future research.

2. Waiter Application

This robotic application, which simulates the behaviour of the whole body of a waiter while trying to transport drinks or food on a tray, is inspired in the real world. The choice of using a humanoid robot to be a waiter could arouse a question: Why giving preference to the use of a humanoid robot instead of a mobile robot?

At first sight, a mobile robot could seem to be the best choice to transport drinks from one place to another because of their wheels. But as it is well known by everybody, the environment in which we move is adequate to our anthropomorphic qualities. Therefore, as it can be seen in Figure 2, we can find for example stairs to overcome a slope, which a mobile robot is not capable of overtaking.

Figure 2: Complex environments adapted to humans' physiognomy: Stairs to go to the second floor, narrow zone where people are sitting, step to go out to serve in the terrace.

In addition, we can find previous examples in which humanoid robots have been chosen to serve people, for example the ASIMO robot (Khil y Lee, 2014). We also have to take in account that in a wet surface the wheels of a mobile robot could slide, causing a poor performance.

However, a humanoid robot has the capability of bending its knees having a lower Centre of Mass (CoM) to acquire more equilibrium. Furthermore, it can balance its body to avoid any falling or walk slowly, or even use its arms to maintain the equilibrium. For example, the HRP-2 is capable of walking over wet floors (Kaneko et al., 2005).

To reach the target proposed in this work, we have considered that the robot has to perform three main tasks. The goal of the first one is to maintain the balance of the object to be transported over the tray while the robot is in repose.

In the second one, the aim is to maintain the equilibrium of the robot and of the objects over the tray while it is moving from one point to another. Finally, has to be capable of walking and keeping the object balance at the same time.

To define the application, we have taken into account the morphological aspects related to a human waiter. Human beings use their own proprioceptive sensors to sense their equilibrium state and to perform locomotion tasks. In the case of the robot, these proprioceptive sensors are the visual, inertial, position and force-torque ones.

On the one hand, these sensors are also necessary to develop manipulation tasks, as far as it is important to sense the arm's state to control the pose of the drink over the tray. We also have to notice that human begins use their eyes to detect the equilibrium state of the drinks or bottles on the tray and to correct the pose of the arm to maintain the stability. In this case, it is proposed that the robot uses the camera and the force-torque sensor in its wrist to verify it and close the loop.

On the other hand, taking advantage of the mathematical model of the robot, it is necessary to propose a system for controlling the balance of the whole-body humanoid robot. This system should take into consideration the equilibrium state of the humanoid robot and the influences/perturbations generated during the task of manipulation.

The investigation has been carried out in the area of compliant control of humanoid robots with focus on the design and execution of complex manipulation skills. To summarize, the global goal of the thesis developed is to integrate, both the body balance of the humanoid robot and the object balance in a non-grasping task, in a unique system capable to transport that object from one point to another without losing both controls, as can be shown in Figure 3.

If we go deeper into this figure, the parts marked with the number 3 are related to chapter 3. In this one, the need to treat the visual information of the camera is explained. In this way, visual problems will be reduced and the object balance control cab be more robust.

The parts marked with the number 4 are related to chapter 4. In this one, the problems arising from the mechanics of the robot are introduced. They move to the force-torque sensors, but through an experimental method, the body balance control can be adjusted to eliminate these errors at each work point.

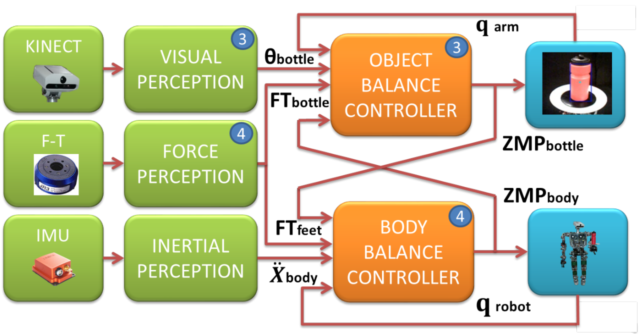


Figure 3: The whole-body humanoid robot architecture control to develop the waiter application.

In particular, we must address the important subject of whole-body control based on hybrid sensory systems related with postural, inertial, force-torque and vision control, and the synthesis of whole-body skills using optimal postural primitives. In essence, based on fusion sensor, a complex whole-body kinematic and dynamic model for service tasks, a body balance of a humanoid robot and a manipulation balance oriented to object transport tasks are described.

To achieve these objectives, the following two chapters show investigations carried out related to the treatment of sensory information. The sensor fusion will have a greater success and therefore the balance controls thanks to these last two achievements.

3. Development of the Visual Perception

New applications related to robotic manipulation or transportation tasks, with or without physical grasping (Chua et al., 2014; Salganicoff et al., 1996; Ohno et al., 2011), are continuously being developed. To perform these activities, the robot takes advantage of different kinds of perceptions. One of the key perceptions in robotics is vision.

However, some problems related to image processing makes difficult to control the robot application with visual information algorithms. The first one is the need of performing a very fast data treatment to obtain the input data for the controller from the raw data from the sensors. The second problem is the existence of errors added to the sensor data caused by the camera defects and the perspective (Schmieder et al., 2013).

As a waiter robot, one of TEO's application is transport an object which it is not linked to the robot through a rigid union or joint (in this case, a bottle on a tray). Because o f that, it is more difficult to ensure a proper transportation task (object balance control). In this research, the inclination angle of the object is obtained from the visual system of the robot.

However, this information cannot be used directly. It contains inaccuracies (Kumar et al., 2010; Wu y Yu, 2005). Therefore, it is important to obtain this feature with a high level of accuracy in order to be capable of achieving a stable control of the bottle. In this work, a Fuzzy filter trained by ANFIS (Adaptive Neuro-Fuzzy Interface System) is proposed (Qi et al., 2016; Prado et al., 2012). It is able to deal with the errors of the system and reduce the computing time at the same time.

To remove the errors caused by the perspective deformation and the ones caused by the camera lenses, an experimental setup has been defined. First of all, the information needed to train the Fuzzy filter has been obtained. To acquire the data, several sweeps have been done, positioning the bottle in front of the robot camera and obtaining *n-Images*.

These sweeps were done by configuring the bottle in controlled and known inclination angles. Moreover, knowing the real angle of the bottle, it is possible to have knowledge of the error, which is introduced in each position of the image.

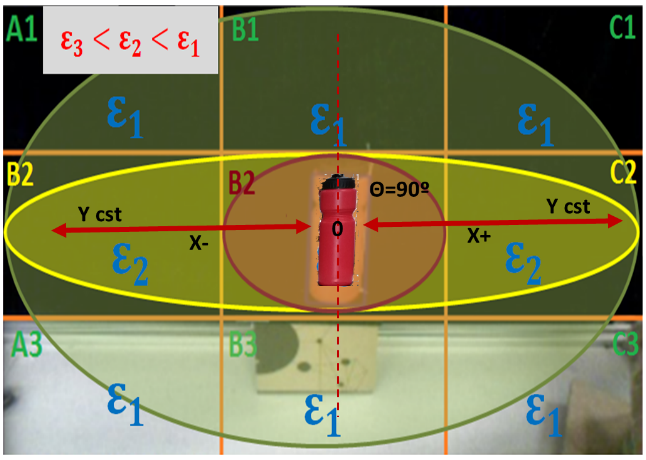


Figure 4: Selection of the Error Priority in the different quadrants of the Image. Moreover, it is shown the position range ob the bottle during the first experiment validating the Fuzzy filter with 90 degrees inclination angle as input.

With all of this information, both a *Training Dadaset* and a *Checking Dadaset* have been created. A total of 50 samplings in a wide range of positions have been made, acquiring more than 20,000 data points. Through the ANFIS, Fuzzy filter is trained and checked with the information of the error regarding each of the positions set in the dataset (Figure 4), and it is capable of doing a correction in the new information obtained with the camera.

In this first experiment, several sweeps in the central horizontal row of the image has been done (Figure 4). During these sweeps, the bottle was maintained fully straight, with an angle of 90 degrees in relation to the horizontal plane, keeping the bottle straight and keeping the axis of the pixel coordinate Y constant. After having post-processed the information with the Fuzzy filter, the error was corrected and the 90 degrees angle has been obtained.

This corrected information is shown by the red line. As it can be seen in the Figure 5, this red line is really close to 90 degrees. Knowing that the experiment has been performed with a real angle of the bottle equal to 90 degrees, we evaluate the higher value of the red line and calculate that the error of the system in this experiment is not higher than 0.0172 degrees.

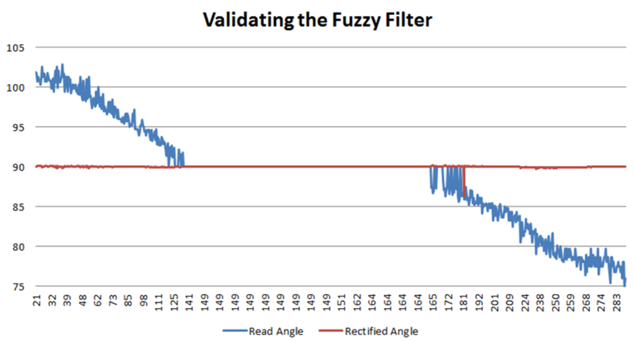


Figure 5: Angle inclination of the bottle before and after to apply the Fuzzy filter for the first experiment.

This second experiment has been carried out by positioning the bottle in different inclinations, which were also controlled and known. The goal pursued in this second experiment is to test if the Fuzzy filter is also capable of properly rectifying the visual data obtained.

As can be seen in the results shown in Table 1, the angle obtained firstly by the camera differs from the real one. However, once the information has been processed, the results of the inclination angle of the bottle are quite similar to the real tilt angles of the bottle.

4. Humanoid Balance Model Adjustment

The computational complexity of humanoid robot balance control is reduced through the application of simplified kinematics and dynamics models. But, these simplifications lead to the introduction of errors that add to other inherent electromechanic inaccuracies (Jung-Hoon Kim y Jun-Ho Oh, 2004) and affect the robotic system. Linear control systems deal with these inaccuracies if they operate around a specific working point but are less precise if they do not.

Table 1: Results obtained after having processed the information through the Fuzzy filter.

P	Real Angle	Angle Detected	% Err Cam	Angle Estimated	% Err Fuzzy
P1	81	68.15	15.83	86.66	6.9
P2	81	93.01	14.83	84.32	4.1
P3	99	83.40	15.75	89.78	9.3
P4	99	107.3	8.43	86.90	12.2
P5	87	74.05	14.87	87.43	0.5
P6	87	98.74	13.50	89.73	3.1
P7	93	76.75	17.46	90.05	3.2
P8	93	103.3	11.17	90.57	2.6
P9	90	91.16	1.29	90.22	0.2

On the one hand, in a balance control system, the concept of the "simplified model" implies the assumption of errors to favour other aspects such as computing velocity, controllability, etc. The simplest model of a humanoid robot used in balance control is the inverted pendulum. Due to its simplicity, it is easy to state that many inaccuracies are introduced and system features are omitted. On the other hand, many improvements and new models have been developed in order to add more information about the robot body or to address the lack of information, such as in (Yin et al., 2006; Lee y Goswami, 2007). In addition, these new models can represent special behaviours or model special tasks (Feng y Sun, 2008; González-Fierro et al., 2016). This research presents one of those improvements for dealing with robot inaccuracies such as material flexibility or component tolerances that are very difficult to model.

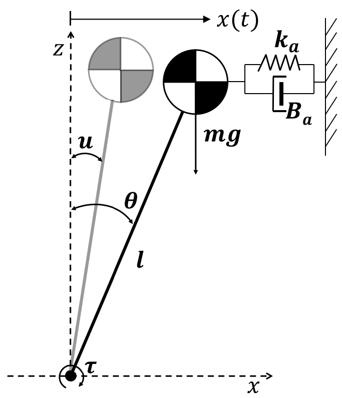


Figure 6: Proposed compensated inverted pendulum model with the additional damping system.

Therefore, this improvement is based on a Linear Inverted Pendulum Model (LIPM) (Kajita et al., 2011) to be applied in a non-linear control system. The aim is to minimize the control error and reduce robot oscillations for multiple working points using the force-torque sensors.

The new model, named the Dynamic LIPM (DLIPM), is used to plan the robot behaviour with respect to changes in the balance status denoted by the zero moment point (ZMP) (Jung-Hoon Kim y Jun-Ho Oh, 2004; Kaynov, 2009). The equation of motion of the DLIPM shown in Figure 6 is given by:

$$\tau = -ml\ddot{x}(t) - B_a l\dot{x}(t) - k_a l x(t) + mgx(t) \qquad (1)$$

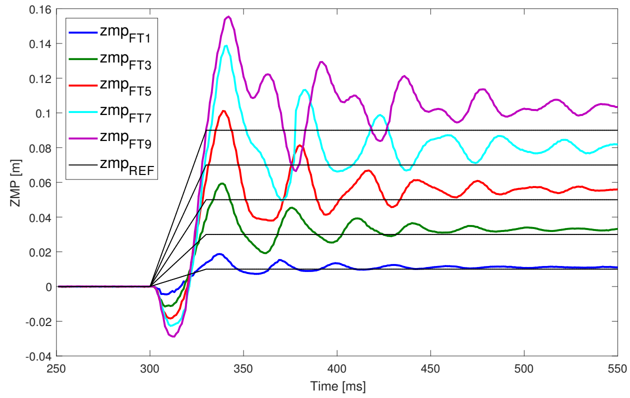
where $x(t)$ is the CoM movement, m is the pendulum mass located at the CoM, l is its longitude, k_a is the spring constant, and B_a is the damper constant.

Thanks to the use of information from force–torque sensors, an experimental procedure has been applied to characterize the inaccuracies and introduce them into the new model. The experiments consist of balance perturbations similar to those of push-recovery trials, in which step-shaped ZMP variations are produced.

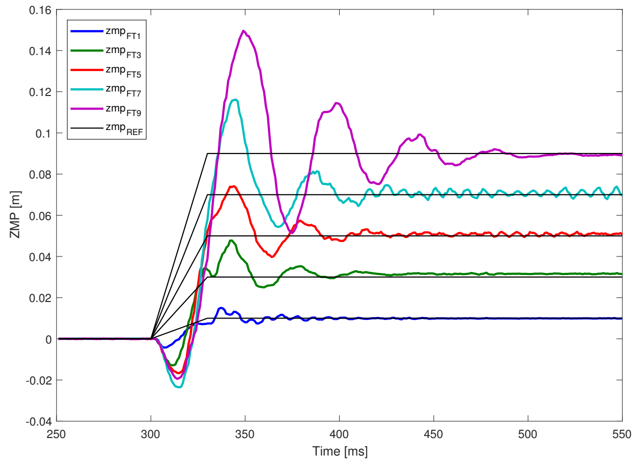
A non-linear solution is proposed based on gain scheduled matching (Kljuno y Williams, 2010; Safiotti, 1997). The main goal is to dynamically select the most appropriate parameters for multiple working points of the controller. That is, the dynamics of the DLIPM model depend on the actual behaviour of the robot and not on pre-computed static parameters.

In this case, there is a preprocessing module for control parameter planning. Depending on the input u, the appropriate values for Ka and Ba can be selected. Then, these parameters are used for computing the rest values of the coefficients of the DLIPM's transfer function. Therefore, these parameters customize and modify, for each control state, the dynamics of the DLIPM model.

It can be observed that the error in the classical system is higher when the ZMP location is further from the initial zero position (ZMP_{LIPM}). Furthermore, the DLIPM curve (ZMP_{DLIPM}) is better adjusted to the desired linear response (ZMP_{REF}). Also, it can be observed that the static error is reduced in each working point (more than 80 % in someone). Moreover, with respect to the dynamic response, it is easy to observe that the level and the duration of oscillations have been reduced. While the overshooting has similar levels in some experiments, the state of the robot is stabilized in general earlier than the classical architecture.



(a)



(b)

Figure 7: Model comparison of ZMP step responses. (**a**) Step response experiments on LIPM; (**b**) Step response experiments on DLIPM.

5. Conclusion & Future Works

After seeing the latest publications made, it can be observed two possible lines of research. The first one is to continue with the non-grasping manipulation control. An the second line of research is to improve the stability control of the robot.

On the first line of research, we want to deepen in the sensory fusion. Once the vision system is improved and more precise, the idea is to integrate it with the force-torque system to have a dynamic control of the bottle. By having a force-torque sensor in the wrist, it can be measured both the forces and the torques generated by the movements of the bottle and the control of the arm. In this way, it will be possible to control the stability of the bottle taking into account the bottle's own perturbations and those ones generated externally (by the body).

The second line of research is related to the combination or coordination of both locomotion and manipulation controls. So far, the robot is able to control its stability through push-recovery strategies. Thanks to the adaptation of the meteoric model used, the robot maintains the balance more efficiently without oscillations or position errors. However, it is necessary to unify the balance control of the object with the control of the whole body. For this, the physics of both systems will be studied. It will be observed if both controllers can be decontrolled or if it is necessary to introduce new entries in the controls that depend on the disturbing tasks.

In this thesis, it is shown the possibility to develop a waiter robot combining/coordinating the stability related with locomotion tasks and the manipulation balance oriented to object transport tasks. It is introduced different method to improve sensory data. The first one based on visual information allows to eliminate both camera and perspective errors in the image. The use os a fuzzy filter trained by ANFIS improves the accurate of visual data and reduces the time complexity of the correction method.

The second one based on a force-torque sensor allows to remove the errors related with material flexibility or component tolerances of the TEO robot. Through a experimental test, it is possible to model the sensor error and generate a new simplified model. This simplified model add a damping system to take into account this errors. The novelty of this method is that the damping system is adjusting dynamical depending on the range of stability of the robot.

As a possible future work to improve the application, you can investigate in the locomotion task. What should it be taken into account to be able to walk and transport the bottle? The influence of starting or stopping the robot on the object, etc.

Spanish Summary

Sistema de Control Orientado a Objetos basado en Fusión Sensorial en Robots Humanoides para Tareas de Transporte.

Resumen

Cade vez se están usan diferentes sistemas robóticos en el campo de los robots de servicio. El tipo de robot más complejo dedicados a estas tareas de servicio son los robots humanoides. Pero al mismo tiempo, estos robots son los más versátiles. Esta tesis presenta el uso del robot humanoide TEO (Task Environment Operator) como un robot camarero. En este caso, el robot intentará imitar a un camarero. Por lo tanto, en esta investigación, hay dos objetivos principales. El primero está relacionado con la tarea de transporte. La idea es aprender cómo un robot humanoide debe manipular y transportar objetos sin un agarre físico. Lo más importante será mantener el equilibrio de objetos con un sistema de control apropiado para tratar con esta aplicación de servicio específica. El propósito es entender la física del movimiento para el equilibrio del objeto a través del uso de la fusión de la información de los sensores. El segundo objetivo está relacionado con el control de equilibrio de todo el robot y los efectos de este control sobre la tarea de manipulación. Aplicando diferentes estrategias de “push-recovery”, el robot debería ser capaz de mantener su estabilidad y la del objeto transportado a la vez.

Palabras Clave:

Manipuladores Robóticos, Estabilidad, Fusión Sensorial, Control.

Acknowledgments

The research leading to these results has received funding from the RoboCity2030-III-CM project (Robótica aplicada a la mejora de la calidad de vida de los ciudadanos. Fase III; S2013/MIT-2748), funded by Programas de Actividades I+D en la Com. de Madrid and cofunded by Structural Funds of the EU.

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