Master Thesis

Máster en Robótica y Automatización

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Balance control of humanoid robot TEO using Force/Torque sensors

Author:

María Dolores Pinel del Valle

Director:

Santiago Martínez de la Casa Díaz

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

Industry was one of the first fields of application of robotics, where the environment is mainly static, the tasks to be performed are repetitive and automated, and the human interaction is quite low. For that reason, the idea of designing robots able to work in dynamic environments, with a high variety of tasks and interacting with humans and their environment, was fullfilled thanks to the evolution of new techniques related to robotics. Humanoid robots, physically similar to the human being, meet all that needs. Mainly, the possibility of moving, solves the problem of industrial robots that can only work in fixed areas. Moreover, the provision of artificial intelligence, allows the robot to interact with the surrounding environment in a more natural way, as the human being.

Nevertheless, the posibility of moving, brings Sin embargo, la posibilidad de desplazarse trae consigo una gran problemática, la estabilidad. El hecho de que el robot se mantenga erguido y camine, es una tarea complicada desde el punto de vista del control. Sin embargo, para el ser humano, el caminar es una tarea que realiza casi inconsicientemente, por lo que no es consciente de su complejidad. En todo momento, se debe asegurar que el robot se mantenga lo más erguido posible para no caer mientras simultáneamente está realizando una serie de movimientos predefinidos para caminar. Asímismo, ante una situación de desequilibrio, un ser humano, involuntariamente, intenta estabilizarse moviendo el resto de extremidades, lo que es un complicado comportamiento para implementar en un robot.

Los primeros trabajos en cuanto a robots bípedos fueron llevados a cabo sobre 1970 por los autores Kato [?] y Vukobratović. El primer robot antropomórfico, WABOT-1, fue exhibido por Kato en 1973 en la Universidad de Waseda (Japón). Usando un esquema de control bastante sencillo, el robot esra capaz de realizar unos pocos pasos lentos, manteniéndose estable en todo momento. Éste logro, fue el primero que desencadenó la investigación acerca de robots humanoides y de su locomoción.

Paralelamente, Vukobratović y su equipo investigaban en estabilidad para sistemas bípedos en Yugoslavia, basándose en un nuevo criterio de estabilidad, presentado en 1972, como *Zero-Moment Point (ZMP)*. Teniendo en consideración los efectos dinámicos que se producen durante la caminata, desde entonces hasta la actualidad, el criterio de estabilidad del ZMP ha sido el más utilizado en cuanto a robótica humanoide o bípeda se refiere.

El auge de la robótica humanoide comenzó con el desarrollo del robot P2 por la empresa Honda en 1996 [**?**] . El proyecto comenzó en secreto el proyecto diez años antes, tras el lanzamiento del robot WABOT-2 tocando el piano. P2, de 180 centímetros de altura y 210kg de peso, fue el primer humanoide que podía caminar de forma suficientemente estable y cargar con el procesador y la batería a la espalda. Tras éste, los robots P3 y ASIMO fueron sus versiones avanzadas, reduciendo la estatura y el peso del robot.

1.1 Motivacion y objetivos.

Este Trabajo Fin de Máster tiene como principal objetivo realizar el control de estabilidad del robot humanoide TEO (*Task Environment Operator*) utilizando sensores de Fuerza-Par y tratar los problemas y consideraciones que deben ser tenidas en cuenta cuando se diseña el sistema de control de un robot humanoide.

Los objetivos propuestos son:

- Puesta en marcha y adquisición de datos en tiempo real de los sensores de Fuerza-Par acoplados a los tobillos del robot, que serán la principal fuente de realimentación del lazo de control.

- Cálculo de los parámetros de estabilidad de interés, entre ellos el ZMP *Zero-Moment Point*, y evaluar en funcion de éstos la estabilidad o no estabilidad del robot.

- Diseño de un sistema de control realimentado que permita rectificar los parámetros de estabilidad mencionados anteriormente, y por tanto, la postura del robot para lograr una mayor estabilidad.

Chapter 2

Literature review

The control of humanoid robots which are supposed to interact with the surrounding environment including human presence is a complex task which has to be divided, e.g., controlling locomotion separately from manipulation. A principal aspect in locomotion is stability or balance control, which avoids the humanoid to fall over during a walk pretending to imitate the human walking.

This chapter will provide a brief introduction about humanoid stability control, the bases of biped walking and essential concepts such as *Zero-Moment Point (ZMP)* and its extensions.

2.1 Biped locomotion

Robot walking, as humans, is performed in a three phase cycle (Fig. 2.1). The cycle is divided in two, left and right steps. At the begining, the humanoid is in a stable position with both feet on the ground (Fig. 2.1 (a)) and all the body weight is transferred form one foot to the other. Then the step generation starts when the right foot leaves the ground in the swinging phase (Figura 2.1 (b), (c) y (d)). After the right foot touches the ground, the next (right) step with the same basic phases is started, and the whole cycle ends. The single-support phase is the complex one in terms of balance, because all the weight remains in only one support foot.

Swinging phase has also three sub-phases: acceleration, swinging and deceleration (Fig. 2.1 (b), (c) y (d), respectively). The acceleration phase takes its name due to the acceleration of the lifting leg that stops being supported in the ground and gives the impulse to the step. Once the support leg is overtaken, the lifting leg starts the swinging pahse in order to reach the ground with the consequent deceleration.

As in the case of the leg, the same occurs with the foot, what adds complexity to control

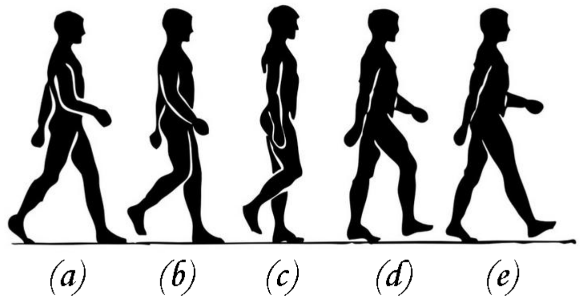


Figure 2.1: Phases of biped walking.

the walking cycle. During a gait, a human foot has four different phases as one can see in Fig. 2.2. In (a) it is shown how the body weight is supported when the heel is touching the ground. In (b), the foot remains totally plane. In (c), the heel lifts and the weight goes to the front part of the foot. Finally, in (d) the foot is not in contact with the ground and it starts to swing.

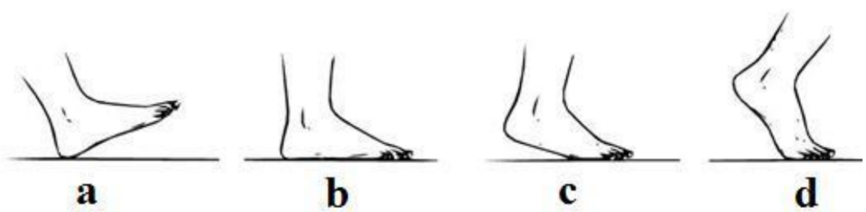


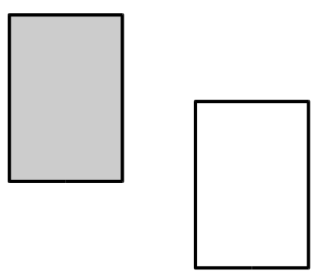
Figure 2.2: Phases of foot support during a walk.

Almost all humanoid robots do not have articulated feet, due to the high complexity. Mostly they use plane and rigid feet and the control is done in the ankle joint. Some of them, as the robot HRP-4 [4], have a joint called "active toe joint" which allows the movement of the toes. The reason of this improvement is related to reach a more natural and fluent walking, as the human walk.

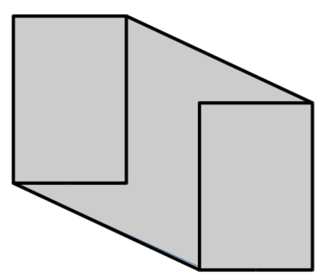
However, in order to perform a stable walk, is not only necessary the lower body movement. The upper body is also involved in recovery movements. In an example, if a person stumbles. Unwittingly, he or she would move the opposite arm of the unbalanced leg, or even more, moving the torso in order to not to fall down. In the case of a biped robot, the same strategy is followed, what means an high increase of the complexity of the control of the robot stability.

2.2 Biped balance/equilibrium

One of the most important and complex tasks for humanoid locomotion is to avoid overturning during the walking or even to reach an upright position of its body. To prevent that, a necessary and suficient condicion is to ensure that there exists a contact area between the foot and the ground and not a line or a point [5]. Given a rectangular-shaped foot, the support area of the robot will be the polygon. In the case that only on foot is touching the ground (single-support), the support area is the contact region between the sole and the ground, i.e., the footprint (Fig. 2.3(a)). On the contrary, when both feet are touching the ground (double-support), the support area will be determined by the footprints and the common tangents between them (Fig. 2.3(b)). It means that in the double-support phase of the walk, the stability area is bigger than in the single-support phase, so the complex of balance control is lower.



(a) Single-support



(b) Double-support

Figure 2.3: Support areas depending on the support type.

In [5], Vukobratović makes a distinction between the term "balance" used in the sense of maintaining an upright posture, and "equilibrium", taking into account the D'Alembert's principle. The D'Alembert's principle states that the resultant of the external forces and the kinetic reaction acting on a body equals zero (condition of kinetic equilibrium). When the humanoid is falling since it is rotating about one foot edge, the D'Alembert's principle still holds for a point on the foot edge where the pressure force acts. Anyway, this case cannot be contemplated as balanced in the sense of the definition previously provided. This point is called as *Center of Pressure (CoP)* and it is known as the point, in a single-support phase, where the pressure forces (normal to the sole) are equivalent to a single resultant force exerted at the point where the resultant moment is zero.

2.3 Zero Moment Point (ZMP)

From the concept of the CoP, appears a new term known as *Zero-Moment Point (ZMP)*. When a human or a humanoid robot executes a gait during a walk, the ZMP is a point inside the support area where, always, the resulting dynamic reaction of the biped system is acting. In a more specific definition, the ZMP is a point inside the support area where the resultant of all forces and torques acting on the full body, is equal to zero.

Vukobratović [5] explains the difference between the CoP and ZMP: CoP and ZMP coincide only when both are inside the support area. When the ZMP goes to the edge of the support area, the humanoid body looses balance and it will fall down. In that case, the ZMP has no sense existing even the CoP.

Goswami [1] presented that, mathematically was possible that the point could be outside of the support area and continue satisfying the equilibrium conditions. This point, called *Foot Rotation Indicator (FRI)*, is defined as the point on the contact area between the ground and the foot, inside or outside the suppor area, where the resultant moment of the forces and torques applied on the foot are normal to the surface. Forces and torques applied mean the forces and torques at the ankle joint, and also other external forces, the foot wheight and reaction forces between the foot and the ground.

However, Vukobratović, on the contrary, stills that the ZMP can only exist inside the support area of the robot. When the ZMP comes close to the edge, any force or moment applied to the system, will produce a rotation about the foot edge and the robot will fall down. In this case, the reaction force of the ground will be at the foot edge and, therefore, it can not be considered as ZMP because there is no stability ensured. That is why the author suggests to denote the point as *Fictitious ZMP* o *FZMP*, if it is outside the support area.

When the robot walking is enough slow to consider almost static, appears the term *pseudo-ZMP*, which is the proyection over the ground of the *Center of Gravity (CoG)* of the system. In such case, lateral accerlerations are so small and can be omitted and the *pseudo-ZMP* = ZMP. Although the *pseudo-ZMP* do not give precise information about the balance of the mecanism, it can be used in order to make a first aproximation in control and design of a humanoid robot.

2.3.1 Equations of ZMP

Let us consider the locomotion mechanism in the single-support phase, with the whole foot being on the ground (Fig. 2.4). To facilitate the analysis we can neglect the part of the mechanism above the ankle of the support foot (point A) and replace its influence by the force F_A and moment M_A, whereby the weight of the foot itself acts at its gravity center (point G). The foot also experiences the ground reaction at point P, whose action keeps the whole mechanism in equilibrium.

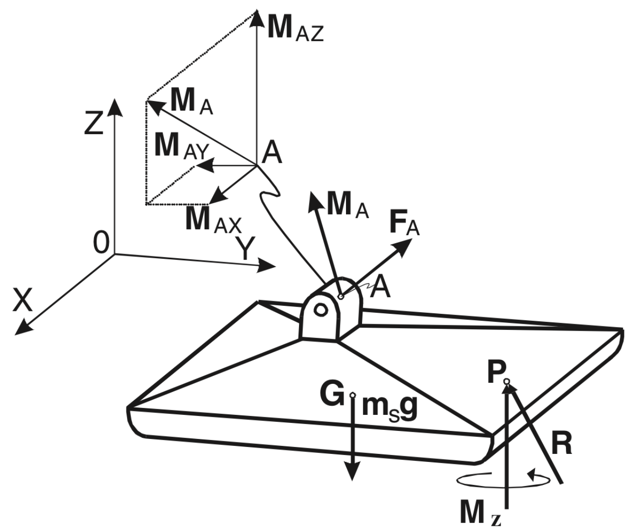


Figure 2.4: Forces acting on the foot of the bipedal mecanism [6].

In general, the total ground reaction consists of three components of the force $R(R_x, R_y, R_z)$ and moment $M(M_x, M_y, M_z)$ exerted at the foot-ground contact point. During the support phase, it is assumed there is no shifting in the contact point, which means that horizontal reaction force R_x and R_y balances the horizontal component of the force F_A, whereas the vertical reaction moment M_z represents the moment of friction reaction forces that balances the vertical component of the moment M_A and the moment induced by the force F_A.

However, due to a unidirectional nature of the connection between the foot and the ground (it is obvious that the ground reaction force induced by foot action is always oriented upwards) horizontal components of all active moments (M_A) can be compensated for only by changing position of the reaction force R within the support polygon. This is illustrated in Fig. 2.5 where a planar case in $y - z$ plane is represented.

The moment M_{Ax} is balanced by shifting the acting point of the force R_z, whose intensity is determined from the equation of balance of all the forces acting on the foot, by the corresponding distance y. It is necessary to emphasize that all the time the reaction force is within the area covered by the foot, the increase in the ankle moment will be compensated for by changing the position of this force R_z, and no horizontal components of the moments M_x and M_z will exist. This is the reason why in Fig. 2.4 at point P only the M_z component exists.

However, if the real support polygon is not large enough to encompass the appropriate

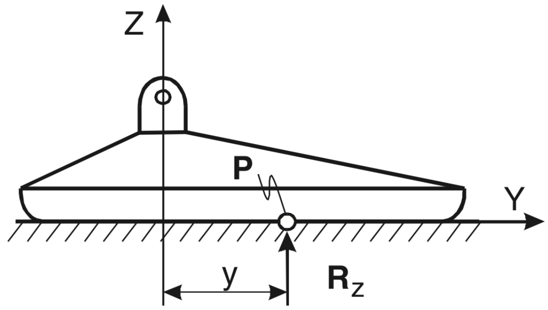


Figure 2.5: Compensación M_{Ax} [6]

position of the force R to balance the action of external moments, the force R will act at the foot edge and the uncompensated part of the horizontal component of the reaction moment will cause the mechanism's rotation about the foot edge, which can result in the mechanism's overturning. Therefore, it can said that the necessary and sufficient condition for the locomotion mechanism to be in dynamic equilibrium is that for the point P on the sole where the ground reaction force is acting,

$$M_x = 0; M_y = 0. \tag{2.1}$$

That is why the *Zero-Moment Point* is called the contact point with the ground (P) where there no exist shifting, i.e., moments M_x y M_y are zero.

From Fig. 2.4 static equilibrium equations for the supporting foot are obtained:

$$\sum \overrightarrow{F} = 0 \Rightarrow \overrightarrow{R} + \overrightarrow{F_A} + m_s g = 0 \tag{2.2}$$

$$\sum \overrightarrow{M_O} = 0 \Rightarrow \overrightarrow{OP} \times \overrightarrow{R} + \overrightarrow{OG} \times m_s g + M_A + M_z + \overrightarrow{OA} \times F_A = 0, \tag{2.3}$$

where $\overrightarrow{OP}$, $\overrightarrow{OG}$ and $\overrightarrow{OA}$ are radius vectors from the origin of the coordinate system O_{xyz} to the ground reaction force acting point (P), foot mass center (G), and ankle joint (A), respectively, while the foot mass is m_s. If we place the origin of the coordinate system at the point P and project Eq. 2.5 onto the z-axis, then the vertical component of the ground reaction momentc (actually, it is the ground friction moment) will be

$$M_z = M_{fr} = -M_A^Z + (\overrightarrow{OA} \times F_A)^Z \tag{2.4}$$

In a general case, this moment is different from zero and can be reduced to zero only by the appropriate dynamics of the overall mechanism. However, the projection of Eq. 2.5 onto the horizontal plane gives:

$$(\overrightarrow{OP} \times \overrightarrow{R})^H + \overrightarrow{OG} \times m_s g + (M_A)^H + (\overrightarrow{OA} \times F_A)^H = 0, \tag{2.5}$$

This equation is a basis for computing the position of the ground reaction force acting point (P) which gives the ZMP position.

2.3.2 Relation between COG and ZMP

When a humanoid robot is in the single-support phase during a walking cycle, its dynamics can be represented by a single inverted pendulum where the supporting foot is the point where all body mass is concentrated (COG) and a mass less telescopic leg [2]. The pendulum can increase or decrease its length, thus simulating the functioning of the ankle joint.

Now, let us consider that the inverted pendulum instead of only one contact point considered above, has a contact polygon as the surface in contact with the ground (Fig. 2.6).

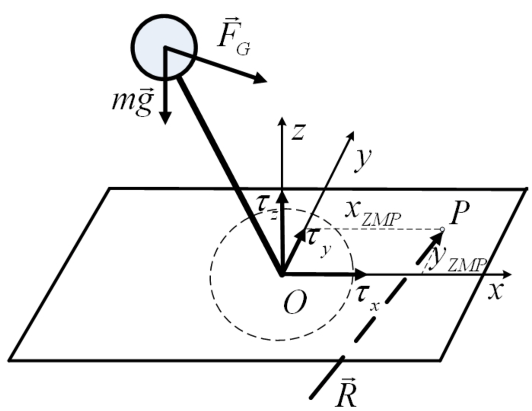


Figure 2.6: 3D Linear Inverted Pendulum with a contact polygon. CITA

Inertial $\overrightarrow{F_G}$ and gravity $m\overrightarrow{g}$ froces act on the point mass located in the COG of the humanoid robot. The contact of the pendulum with the ground produces a reaction force $\overrightarrow{R}$ and reaction moment $\overrightarrow{M_P}$ at point P For any other point of the support polygon (taking point 0 as origin), the moment $M_0 = [\tau_x, \tau_y, \tau_z]^T$ produced by the ground reaction force $\overrightarrow{R}$ is represented:

$$M_0 = M_P + \overrightarrow{0P} \times \overrightarrow{R} \tag{2.6}$$

If it is considered point P to be the ZMP of the system, then from the interpretation of the ZMP presented above $M_P = 0$. In this case we can denote vector $\overrightarrow{OP} = [x_{ZMP}, y_{ZMP}, z_{ZMP}]^T$

and eq. 2.6 gives the following equation:

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} x_{ZMP} \\ y_{ZMP} \\ z_{ZMP} \end{pmatrix} \times \overrightarrow{R} \tag{2.7}$$

From the other side, applying Newton's law of mechanics to system in Fig. 2.6:

$$m\overrightarrow{a_G} = \overrightarrow{R} - m\overrightarrow{g} \tag{2.8}$$

where $\overrightarrow{a_G} = [\ddot{x}, \ddot{y}, \ddot{z}]^T$ is the acceleration of the COG. From 2.8 it is obtained:

$$\overrightarrow{R} = m \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} + g \end{pmatrix} \tag{2.9}$$

Substituting equation 2.9 into the equation of balance of moments 2.7 it is obtained:

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = m \begin{pmatrix} x_{ZMP} \\ y_{ZMP} \\ z_{ZMP} \end{pmatrix} \times \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} + g \end{pmatrix} \tag{2.10}$$

After a cross product and taking into account that $z_{zmp} = 0$, because the ZMP lies into the ground:

$$\begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix} = m \begin{pmatrix} y_{ZMP}(\ddot{z} + g) \\ -x_{ZMP}(\ddot{z} + g) \\ x_{ZMP}\ddot{y} - y_{ZMP}\ddot{x} \end{pmatrix} \tag{2.11}$$

From (2.11), it can be stated the ZMP position of the system:

$$x_{ZMP} = -\frac{\tau_y}{m(\ddot{z} + g)} \tag{2.12}$$

$$y_{ZMP} = \frac{\tau_x}{m(\ddot{z} + g)} \tag{2.13}$$

If it is supposed that the COG always remains within the horizontal plain intersecting the z axis in the point z_c (one of the constraints of the 3D-LIPM model), then the vertical component of the COG acceleration $\ddot{z} = 0$. Then, finally, equations 2.12 and 2.13 take the form:

$$x_{ZMP} = -\frac{\tau_y + hF_x}{mg} \tag{2.14}$$

$$y_{ZMP} = \frac{\tau_x + hF_y}{mg} \tag{2.15}$$

where h is the distance between the ground and the measuring point, i.e, the height of the sole. These are the *ZMP equations*, without forgetting it was considered before that lateral accelerations of the COG $\ddot{x} = 0$ and $\ddot{y} = 0$. One can see that moments τ_x and τ_y in x and y directions respectively affect the ZMP position of the mecanism and it can loose balance because of their change.

If we take into account these lateral accelerations of the COG, the ZMP can be expressed as a function of the acceleration of the COG as: REFERENCIA?

$$x_{ZMP} = x - \frac{z_c}{g}\ddot{x} \tag{2.16}$$

$$y_{ZMP} = y - \frac{z_c}{g}\ddot{y} \tag{2.17}$$

These equations can only be applied to compute ZMP in single-support phase. In the case of the double-support phase, it is necessary to calculate the weighted average of the sensor measurements form both feet as recommended in [3]. Therefore, the resulting equations for ZMP in double-support phase are:

$$x_{ZMP} = -\frac{F_y^R \cdot x^R + F_y^L \cdot x^L}{F_z^R + F_z^L} \tag{2.18}$$

$$y_{ZMP} = \frac{F_x^R \cdot y^R + F_x^L \cdot y^L}{F_z^R + F_z^L} \tag{2.19}$$

where the upper index R represents the right foot and L the left one. Revisar si el numerador es par o fuerza.

2.3.3 ZMP areas.

As mentioned before, ZMP is a point in the sole which depends on the forces and moments applied to the robot. Therefore, depending on the magnitude of that forces, ZMP will change and it becomes a dynamic parameter. As suggested in [5], three regions are defined depending on the position of the ZMP as one can see in Fig. 2.7. In the balanced area (safe region), the control action will not actuate. In the nearly critical region, the control action will actuate as a secondary solution. This may be the case of a walking task. As humans do, the robot may use its arms in order to reduce the zero-moment point position closer to the safe region. Finally, in the critical region, the stabilizer will actually disconnect the ongoing task and actuate on the full body. Even if this region is still stable, the balance may be easily lost.

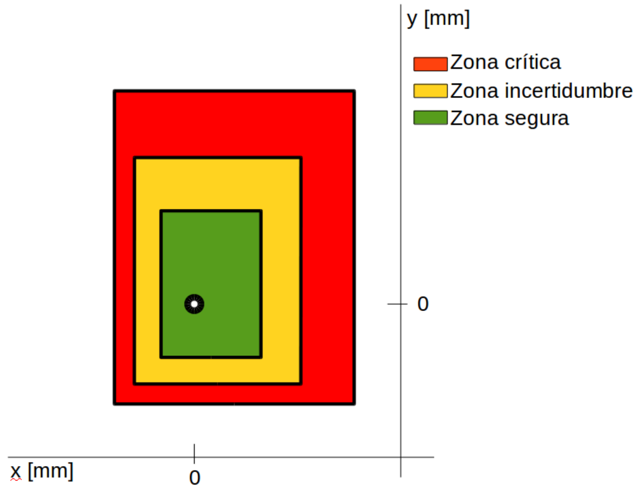


Figure 2.7: ZMP stability regions in single-support.

2.4 Biped modeling

Chapter 3

Platform description

3.1 Humanoid robot TEO

El robot humanoide RH-2, también conocido como TEO (Task Environment Operator), de la Universidad Carlos III de Madrid, es una versión avanzada de los humanoides RH-0 y RH-1.

El RH-2 tiene una altura de 165cm que supera los 150cm del RH-1 y los 120cm del RH-0. Su peso es de, aproximadamente , 60 kg y se estima que puede soportar objetos de hasta 2kg.

Cuenta con 24 GDL (26 GDL teniendo en cuenta los motores de la cabeza), los cuales son 3 grados más que las anteriores versiones de RH. En la Figura **??** se muestran los grados de libertad del robot, además del el tipo de movimiento que realiza cada uno, siendo 6 GDL para cada pierna, 6 GDL para cada brazo, 2 GDL en el torso y 2 GDL en la cabeza.

El robot consta de 4 microprocesadores, uno encargado de la locomoción, otro encargado de la manipulación, otro encargado de realizar las tareas de visión artificial y por último, un procesador central que gestiona el resto. El procesador encargado de la locomoción, que controla las piernas y el torso, se encargará de procesar la información de los sensores para lograr que el robot mantenga y el equilibrio, y por consiguiente, realize una caminata estable. Por su parte el procesador manipulador se encargará de contolar el movimiento de los brazos y de la cabeza. El procesador encargado de la visión por computador opera utilizando una cámara con sensor infrarrojo ASUS incorporada en la cabeza.

El sistema de comunicaciones sigue el protocolo CAN-bus realizando una división sagital y transversal del humanoide, existiendo 4 líneas de CAN-bus. Una línea CAN se encargará de comunicar el brazo izquierdo, mientras que otra se ocupará del lado derecho. Igualmente, en el tren inferior, una línea can se ocupará de la pierna izquierda y otra de la pierna derecha.

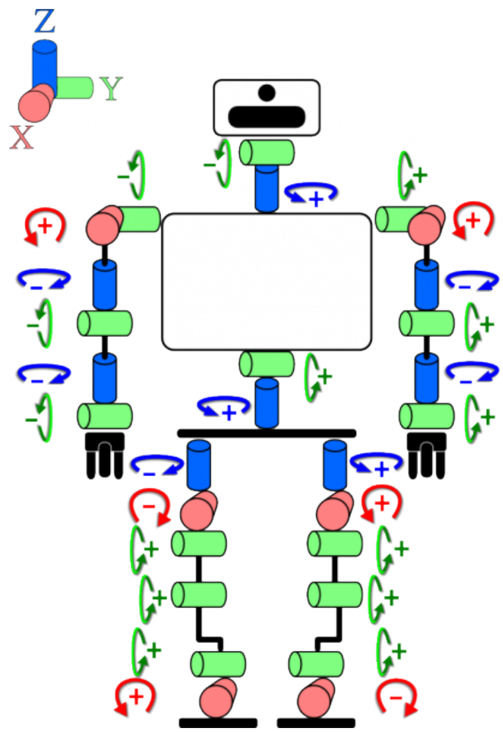


Figure 3.1: Distribución de grados de libertad del robot TEO.

A su vez, para realizar la adquisición de datos de los sensores de Fuerza-Par que lleva incorportados en los tobillos -y que serán utilizados para realizar una caminata estable-, se utilizan tarjetas de adquisición de datos PCI que trabajan en tiempo real. Con un sensor en cada tobillo, el robot dispone de dos tarjetas PCI en el procesador del tren inferior. Del mismo modo, para las tareas de manipulación se utiliza un sensor Fuerza-Par en cada muñeca conectados a través de una PCI con el procesador del tren superior.

La dotación de sensorización de fuerzas y momentos es una importante diferencia respecto a los antecesores del robot RH-2. La utilización de estos sensores, permite cerrar el bucle de control -y así, obtener realimentación-, que tan necesario es para realizar una caminata estable.

3.2 Force/Torque sensors

Los sensores Fuerza-Par (F/T) utilizados están basados en sensores extensiométricos dispuestos de tal forma que permiten obtener medidas de fuerza y momentos en los tres ejes del espacio tridimensional.

Los sensores de los que dispone el robot son los sensores comerciales JR3 descritos en la Tabla 3.1. Obsérvese la diferencia de fondo de escala de los sensores utilizados en las articulaciones de los tobillos a los de las muñecas. Los sensores de los tobillos tienen que ser capaces de soportar fuerzas y momentos mucho mayores incluyendo las que ejerce el propio cuerpo del robot.

Articulación	Modelo	$F_{x,y}$	F_z	$M_{x,y,z}$
Muñecas	50M31A	100N	200N	5 Nm
Tobillos	85M35A	250N	500N	212Nm

Table 3.1: Modelos y características de sensores F/T del robot. *Fuente: JR3 Inc.*

Según el fabricante, los dos primeros dígitos del modelo indican el diámetro del sensor, la letra que les sigue la serie, y los dos siguiente dígitos el espesor del mismo. De ahí, los sensores de los tobillos tendrán un diámetro de 85mm, un espesor de 35mm y es de la serie M.

Los sensores M incluyen electrónica interna para filtrar el ruido, salida digital para la utilización de una tarjeta de adquisición de datos PCI del mismo fabricante y opción de salida analógica. La exactitud nominal de todos los sensores de esta serie es del 1% de fondo de escala, y una resolución de 1/4000 del fondo de escala.

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