ROBIP: A SOFTWARE PACKAGE FOR THE EXPERIMENTAL EVALUATION OF THE REQUIRED DEGREES OF FREEDOM FOR A BIPED ROBOT

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Abstract: There is a real need for machines that can replace humans in hazardous occupations. Since most work sites have been designed for human workers, any machine which is to perform the same tasks as humans must have the same dexterity. This article presents a software package which permits the observation and analysis of the gait employed by human beings. The minimum number of degrees of freedom which are necessary for achieving the human agility is determined from a theoretical point of view. Later, a brief description of the software tool is presented, and finally, the results of experimentation are shown.

Keywords: Robotics, mobile robots, simulation, stability, agile control, walking.

1. INTRODUCTION

As it is well-known, the optimum number of degrees of freedom of a biped robot (Sias, Zheng, 1990), is still an open point, since it depends on several considerations, i. e., the final use of the biped.

A biped robot is a potential solution to the need for locomotion in constrained spaces; however, to be of practical use, a biped must be able to stand statically (Sias, Zheng, 1987), while performs useful tasks. For this reason, biped robots have been built with as few as four degrees of freedom per leg.

The aim of this paper is to present a tool for determining the minimum number of degrees of freedom that are required for achieving both simplicity and optimum agility. The proposed tool is a WINDOWS™ application called *ROBIP*, which has been developed in the *Instituto de Automática Industrial (C.S.I.C.)*, and its main purpose is to animate the trajectories obtained by means of an external device, a *motion analyzer*, that acquires data using sensors located at specific joint positions.

2. HOW MANY DEGREES OF FREEDOM ARE NECESSARY TO EMULATE THE ABILITY OF A HUMAN BEING?

One of the primary motivations for designing a biped robot is to perform tasks in environments that are too dangerous for human beings. To be a satisfactory substitute for a human being, the robot must be able to enter a region originally designed for human access and perform tasks that are not already automated and normally require the capability of a person. In many of the previous studies of biped robots, the emphasis was usually focused on locomotion and practical industrial applications are rarely considered. In the author's opinion, to be useful from a practical viewpoint, a biped robot should serve, at least, as a mobile platform. Thus, a practical biped robot should have:

-Static standing.
-Dynamic walking capability.

As it was mentioned before, four degrees of freedom per leg (abduction and flexion in both hip and ankle) are enough to obtain a functional biped robot, that is, to maintain the centre of gravity inside the *stability margin* (on uneven surfaces or in the case of external forces tending to topple the biped).

However, additional degrees of freedom are required if the biped robot has to achieve a human-like agility. For example, if the biped robot needs to change walking direction, an additional vertical axis at the hip joint, orthogonal to the other two hip axes is required. On the other hand, sudden discontinuities or steps would pose a significant handicap. A knee joint solves a number of problems associated with traversing uneven surfaces or climbing stairs, which imply extremely awkward shifts of the centre of gravity with four-link legs.

The human ankle is basically a hinge joint with one degree of freedom. However, several tarsal bones combine to produce a joint between the leg and the foot that has three degrees of freedom. Two of these ones are required so that the leg can move in different directions to maintain equilibrium when the hip joints move. In addition, a third degree of freedom with a vertical axis is available to be used to rotate the foot. This extra degree of freedom is unnecessary for most gaits used for locomotion, but could be quite valuable when the biped is in unusual attitudes or on irregular surfaces such as when climbing.

And finally, in this brief overview, let us consider the foot. The human foot is composed of 22 bones that makes it quite flexible and permit several degrees of freedom. The flexion of the foot permits a longer stride with less severe movements of the torso to maintain the centre of gravity over the supporting foot. Hence, a final degree of freedom at the ball of the foot would permit a longer and faster gait.

In short, it can be concluded that a biped robot with eight degrees of freedom per leg could have a gait approximating that of the human being.

3. ROBIP DESCRIPTION

A general block diagram of *ROBIP* is shown in Figure 1.

The software package has three main tasks:

1.-Interface between the *simulation/animation* blocks included in it and:

- other simulation and/or numeric calculation packages, such as MATLAB™ with SIMULINK™.
- HW equipment, i. e. a *motion analyser*.

2.-The calculation of the 3D kinematics and dynamics of a determined mechanical system.

3.-The animation on the screen of the time evolution of a coordinate vector.

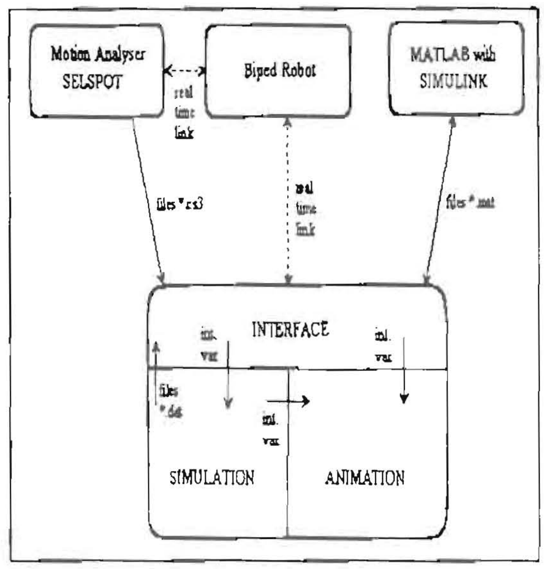

Fig. 1. General sketch of ROBIP.

The dotted lines in Fig. 1 means future implementation, that is, once a biped robot will be available, there will be a *real-time* link to be able to monitor the real motion on the screen, and vice-versa, to command the robot to move in a determined way (*prescribed synergy*). Until now, as a first step, data transfers are made by means of files instead of *real-time* links.

3.1 Interface with the user

As it has been mentioned before, this tool is a WINDOWS™ application, so its interface is based on different *windows*, *buttons*, and *menus* to make it *user friendly*.

The main menu consists of four sub-menues:

-File
-Biped
-Simulation
-Animation

The purpose in this paper is to experimentally determine the optimum number of degrees of freedom to achieve a human gait. So, only the *Animation* block will be used, leaving the *Simulation* for further applications. The data-file source is the SELSPOT II System (opto-electronic motion analysis system) which uses active light sources for determining actual positions of objects in space.

File

All the three kinds of data files that can be loaded by the *ROBIP* package have the common structure that is shown in Fig. 2, where T^{-1} is the sample frequency used for the acquisition of the 3D coordinates of the relevant points selected for tracking the corresponding trajectories.

HEADER with
[frames n][joints m][T^{-1}]

3D coordinates of joints
$x_1y_1z_1\ x_2y_2z_2\ \ldots\ x_my_mz_m$

$$\text{frames}\begin{cases}1T\\2T\\\ldots\\nT\end{cases}$$

Fig. 2. Data file structure

Thus, when the user defines the *Animation Structure* and the *Biped Structure* some initial values will be loaded, such as the number of joints, and the minimum and maximum values of coordinates, for the *auto-scale* mode.

Biped

Once the file has been loaded, the user must define the *biped structure*, that is, the joints and the corresponding links to be animated. The *dialogue window* created to specify this information is shown in Figure 3.

Animation

First of all, the *animation parameters* must be defined (Figure 4):

-*Axis Scale*

-*Animation Mode*, which can be *Continuos* or *Step by Step* (so the animation procedure is controlled by the user).

-*Projection*: the animation can be made in the *sagittal*, *frontal* or *horizontal* plane.

When the Biped Structure and the Animation Parameters has been set, the initial frame of the animation is displayed. Fig. 5 illustrates this fact, showing the obtained structure when using 8 sensors located at different joints of legs, trunk, and arm.

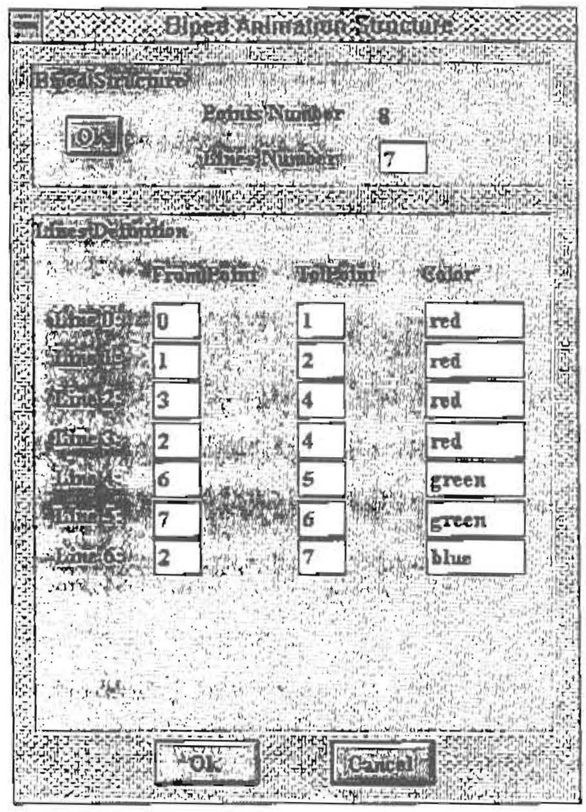

Fig. 3. Biped Structure.

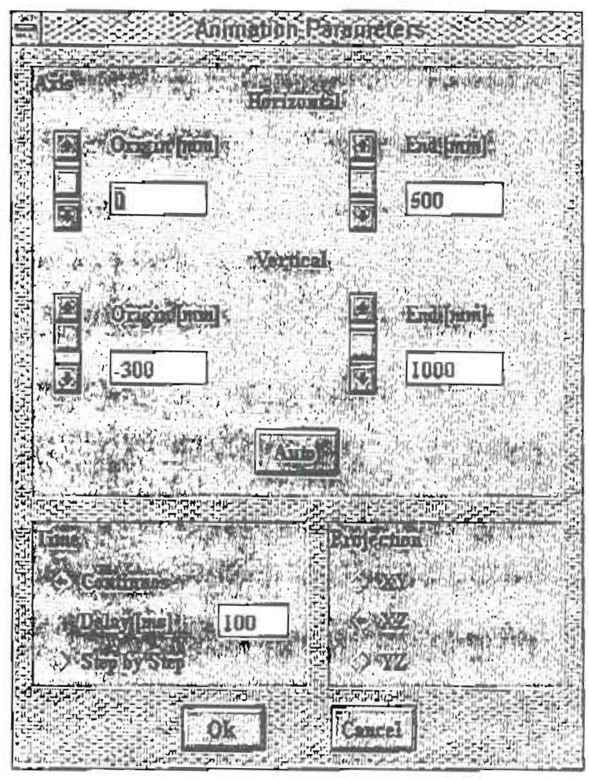

Fig.4. Animation parameters.

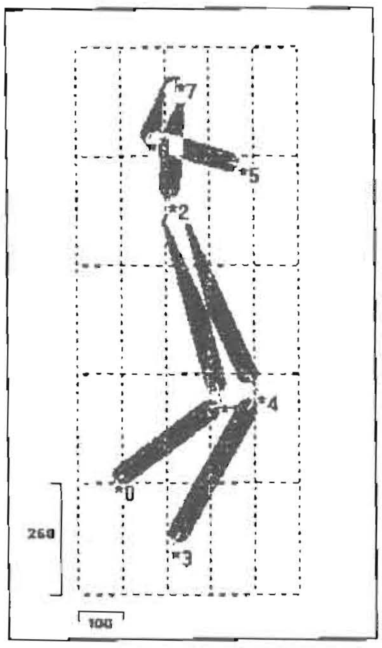

Fig. 5. Initial Frame.

4. PRACTICAL APPLICATION

Experimental measuring tests have been made by means of the SELSPOT II System. Seven *Light Emitting Diodes* were allocated in different ways to obtain the position of the joints in several situations.

4.1 Walking mode

In Figure 6 it is shown a stage of the motion, which is projected on the sagittal plane.

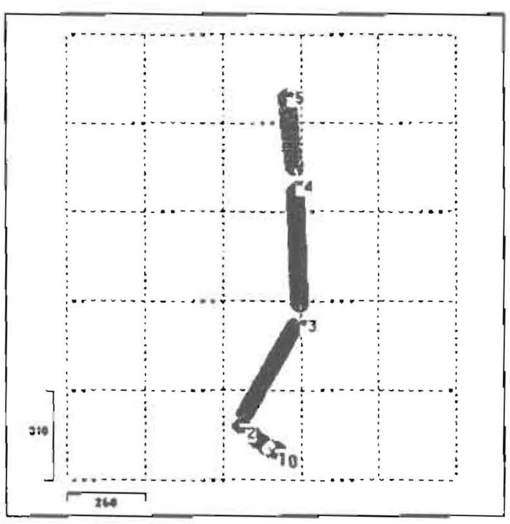

Fig. 6. Walking mode.

0: Tip of the toes	3: Knee
1: Ball of the foot	4: Hip
2: Ankle	5: Shoulder

This configuration corresponds to the *double support phase*, just before the *swing phase* of the leg.

It can be observed that the flexion of the foot plays an important role, since it permits a stance with both feet on the ground during a longer stride while the centre of gravity is shifted to the forward foot. This postural balance can be noticed in the *XY-projection* (Figure 7).

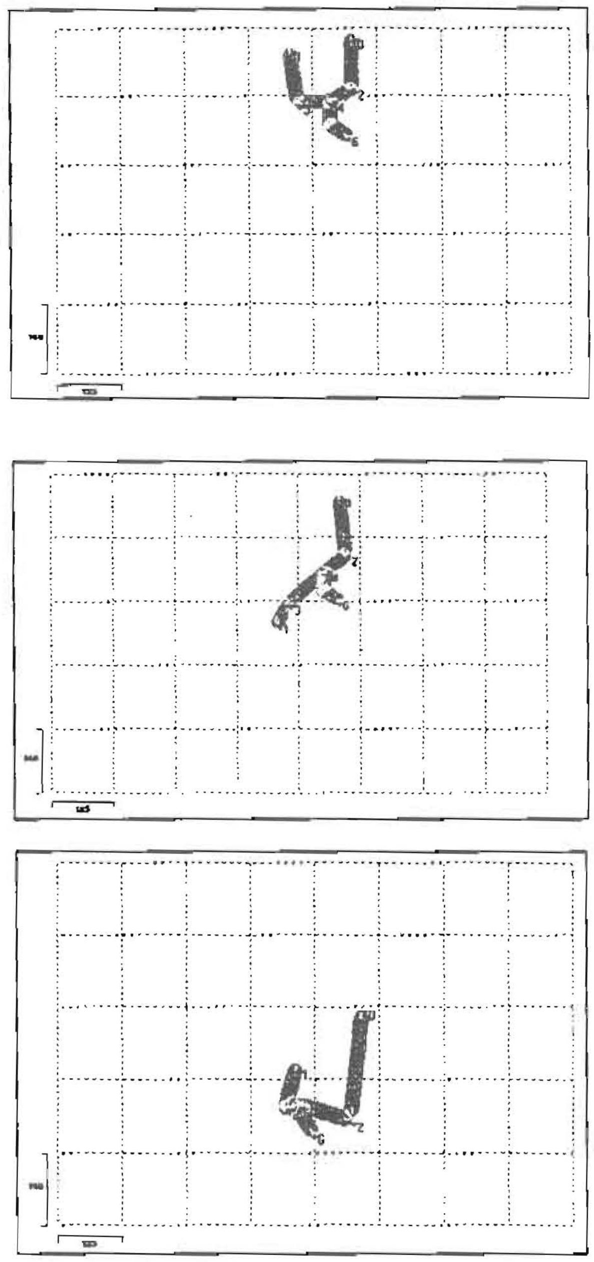

Fig. 7. Walking mode. XY-projection.

0: Left ankle	3: Right Knee
1: Right ankle	5: Chest
2: Left knee	6: Head

When the right leg is in the *swing phase* and the left one is on the ground, the head is near the latter, to keep the centre of gravity on the *stability margin*, and shifts towards the forward leg as this one advances.

4.2 Skipping mode

In this case, a small hop is animated, and three different stages of the motion are shown in Figure 8.

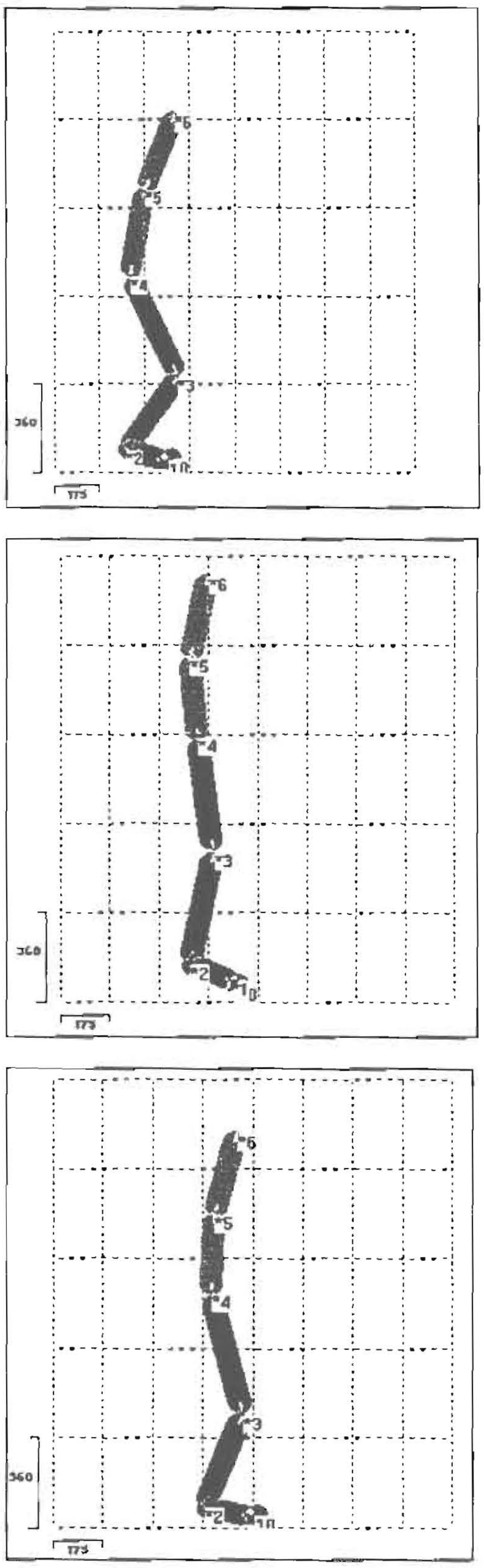

Fig. 8. Skipping mode

Here it can be noticed the relevant roll of the knee and ankle joints in the initial and final stages: in the first one to obtain the impulse which is necessary to lift the body, and in the last stage to absorb the shock caused by the contact with the ground.

4.3 Climbing Stairs mode

In *stair* climbing, frontal plane motions remain almost the same as in normal walking mode (Golden, Zheng, 1990). Consequently, sagittal plane motions are of most importance for this study.

Several experiments were realized dealing with stair climbing. From the results of this experiments, one of them is shown in Figure 9, it is possible to break down the climbing motion into a series of stable phases:

Phase 1:

Starting from a standing position (both feet are on the floor (leveled), Fig. 9-a), this phase consists on shifting the centre of gravity over the left foot and rising the right foot by positive rotation of the right hip and negative rotation of the right knee, as can be seen in Figure 9-b.

Phase 2:

While maintaining the centre of gravity over the left foot, the right foot is positioned over the next step by continued positive rotation of the right hip as well as negative rotation of the right knee (Fig. 9-c).

Phase 3:

The right foot is placed firmly on the step, while the centre of gravity is shifted to the right foot by rotating the torso forward over both hips, as well as to the right (Fig. 9-d).

Phase 4:

The right leg is extended by a positive rotation of the right knee and a negative rotation of the right hip, thus maintaining the centre of gravity over the right foot while raising it in the vertical plane (Fig. 9-e).

From this, it can be illustrated three significant aspects of *stair climbing*: the first aspect is that a much greater range of motion is required than during *level walking*, especially in the knee joint. The second aspect is that *stair climbing* entails an ascending displacement of the centre of gravity. And the third aspect is that a static gait, rather than dynamic, is employed (the vertical projection of the centre of gravity always lies in the enclosed ground area of the supporting foot or feet).

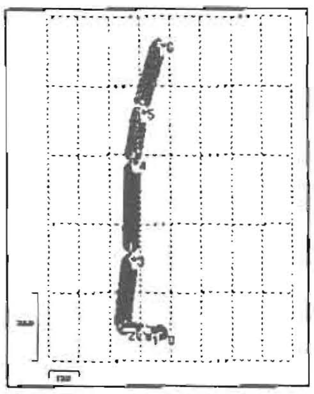

Fig. 9-a

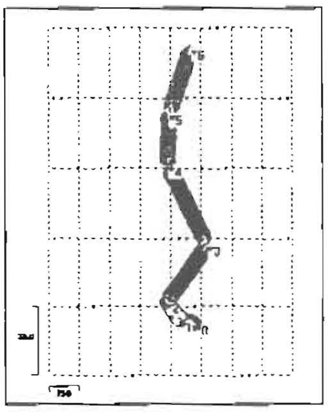

Fig. 9-b

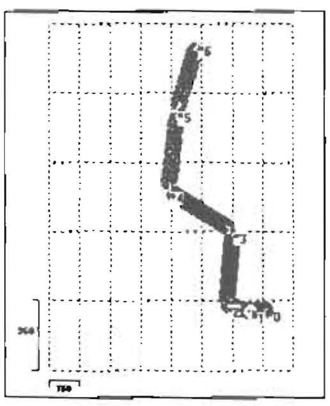

Fig. 9-c

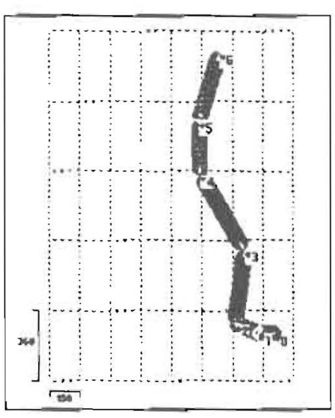

Fig. 9-d

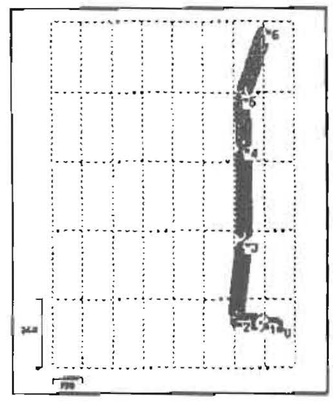

Fig. 9-e

Fig. 9. Stair Climbing Gait (right leg).

5. CONCLUSIONS

In this paper a software package for human gait analysis has been presented. A tool of this characteristics is a good help to determine the number of degrees of freedom required to emulate the human agility under different operational conditions. The role of the different joints has been clearly tested, corroborating the conclusions obtained by theoretical analysis.

6. ACKNOWLEDGEMENTS

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