SENSING WITH A 3-TOE FOOT FOR A MINI-BIPED ROBOT

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Abstract

SENSING WITH A 3-TOE FOOT FOR A MINI-BIPED ROBOT

This thesis describes the implementation of a 3-toe foot for biped robots. The objective is to provide a reliable and low-cost solution for the problem of sensing the center of pressure when stepping over uneven surfaces. To accomplish this goal, a new method for measuring force based on the degree of deflection of a flexural plastic toe is presented. Empirical results confirm that it is possible to obtain the same level of accuracy using this new method than using standard force sensing resistors (FSR).

In order to measure the level of deflection of the plastic toe, a small magnet has been inserted in each toe tip. An arrangement of Hall effect sensors measure the magnetic field generated by the magnet. With the information obtained from the hall effect sensors it is possible to estimate the torques acting on the foot.

In order to obtain a quantitative measurement of the behavior of the system, a set of experiments has been executed. In these experiments, an initial load is applied to the foot, and subsequent variations of extra loads are then applied to modify the location of the center of pressure and the level of torque. The information obtained from the foot is then contrasted with an industrial load cell installed in the ankle of the robot, which provides accurate information regarding the real location of the forces and torques (ground truth). The same experiment has been conducted using a standard commercial FSR foot from Robotis. The results show that the model implemented provides more information, while showing similar accuracy to the commercial model.
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1 Introduction

At bottom, robotics is about us. It is the discipline of emulating our lives, of wondering how we work.

Rod Grupen

Summary. In this chapter, the concept of the center of pressure (CoP), and its relationship with the zero moment point (ZMP), will be briefly explained. In addition, the importance of measuring the CoP in biped robots will be discussed. A new method of measuring the CoP that is both straightforward to implement and inexpensive will be introduced. Finally, other strategies for measuring the CoP will be described.

1.1 Center of Pressure and Zero Moment Point

How to make a stable walking gait. An intuitive goal when one tries to make a machine walk is to prevent it from falling down. Most methods to ensure this condition rely on the so-called Zero Moment Point (ZMP) criterion. The criterion states that, in order to ensure stability in the walking gait, the ZMP must rely within the support polygon. [1]. The ZMP is defined as the point in the ground where the component of the moment tangential to the supporting surface, acting on the biped, due to gravity and inertia forces, equals zero [2]. The support polygon is the convex hull of the foot support points [3]. Figure 3 shows different shapes of the support polygon depending on the posture of the robot. The ZMP method helps avoid falling by ensuring that the robot net forces will always equal a counterpart reaction produced by the floor on its feet, generating equilibrium.

Because of the use of the ZMP as a stability criterion, having the ability of measuring it becomes relevant. It is necessary, however, to define other concepts which will be useful to calculate it.

Fig. 1. Rapid prototyped biped (RPBP)
Same kinematics/actuators as the legs of Darwin-OP[11]
1 Introduction

Fig. 3. Typical shapes of the support polygon in grey. (a) double support. (b) double support with toe-off. (c) Single support. [3]

1.1.1 Center of Pressure CoP

The center of pressure (CoP) refers to a point $p$ (see figure 2) at which, when applying a single resultant force equivalent to the field of pressure forces in the soles of the feet of the robot, lead us to a resultant moment of zero [2].

The definition of CoP is associated to contact forces acting in the feet of the robot. Therefore, in order to obtain the CoP, it is required to use a type of force sensors, generally located in the foot or in the ankle of the biped.

Fig. 2. Ground reaction force acting on the foot of a biped robot [4]
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1.1.2 Zero Moment Point

The ZMP is the point in the ground where the component of the moment tangential to the supporting surface, acting on the biped, due to gravity and inertia forces, equals zero [2]. This definition shows that the nature of the ZMP differs from the nature of the CoP. While the former comes from gravity and inertia forces, the latter comes from pure contact forces.

Given that the ZMP is affected by inertias and gravity, the procedure to calculate it involves precise knowledge of the mass, inertia, center of mass, and acceleration of every link of the body of the robot. Summing the contribution of every link, and using forward dynamics, it is possible to calculate the ZMP. This procedure is not always desirable because of its computational cost and/or the complexity of calibrating and sensing the state of the dynamical model.

1.2 Relationship between CoP and ZMP

Despite of the popularity of the concepts of ZMP and CoP and their common use in the control of biped robots, sometimes their direct relationship is not clear. Some authors define those concepts with partial similitude restricted to certain conditions [5], and some others do not make any distinction between them [6].

Although the concepts of CoP and ZMP are very different, it has been shown in [2] that - if the robot is walking in a planar surface - the CoP and the ZMP will always coincide. Furthermore, the authors in [2] also demonstrated that this equality can be extended to the case of walking on uneven surfaces by defining a virtual surface.

These results simplify the calculation of the ZMP. All we need is to measure the contact forces on the feet of the robot (CoP). Using feedback control to ensure that the ZMP will always remain within the support polygon will ensure a stable gait.

1.3 A new method for sensing the CoP

The purpose of this work is to present a new method for sensing the CoP, which makes use of the deflection of the 3 toes of a flexural foot for measuring the forces acting on it. Once forces are obtained, the CoP is calculated as the weighted average of the vectors representing those forces. Figure 4 shows the prototype of the 3-Toe foot.
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The white pieces in this prototype are 3D printed ABS plastic from a Stratays FDM machine. Other flexural materials including metals could be used depending on desired stiffness.

Fig. 4. The 3-Toe foot. Cost USD $115. Weight 0.053 Kg. Dimensions 64x100x30 mm

Hall effect sensors measure the magnetic field emitted by magnets located in each toe. The relative position of each toe is proportional to the force applied to it. Variations in force yield to variations in position of the magnets, which are detected as changes in the magnetic field. Applying function fitting methods, the weight values for the weighted average are obtained, and the CoP is calculated. Experimental data confirm the functionality of the model, which shows the same level of accuracy as force sensing resistor (FSR) sensors, the prior state of the art for low-cost CoP sensing (see section 1.4.2). A six-axes load cell installed in the ankle can also measure CoP precisely (see section 1.4.1) but can be about 50 times as expensive. In our experiments we use such load cell for reference. The system and its functionality will be described in depth in chapter 2.

1.4 Other methods for sensing the CoP

Given the importance of the CoP in the implementation of stable walking gaits on biped robots, several methods have been developed to measure it [4,7-10]. These differ in accuracy, size, weight, capability of measuring different variables, and cost.
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1.4.1 Universal Force-Moment Sensors (Load Cells)

One of the most accurate methods to measure the forces acting in the limbs of robots is the use of universal force-moment sensors (UFS), also known as load cells. UFS measure 3 forces and 3 torques in x-y-z, and are widely used in industry to control the motion of robotic arms in automated processes. When cost is not a concern, UFS can be the preferred method to measure CoP in biped robots [7].

Although UFS are one of the most accurate sensors available, they have some disadvantages. Given their dimensions and design, most UFS are installed in the ankle of the robots, and some calculation is required in order to obtain the measurements of forces and torques in the plane of the sole of the foot. Also, the cost of these sensors is very high. The mini-biped robot used in this work (refer to figure 1) cost about $5k. Installing commercially available UFS in each ankle would alone cost about $15k.

![Fig. 5. Load Cell. Model Nano25. Diameter/ height 28mm. Mass 0.136kg, Manufactured by ATI Industrial Automation.](image)

1.4.2 Force Sensing Resistors (FSR)

An alternative to measure the CoP at a low cost is the use Force Sensing Resistors (FSR). FSR are thin polymer film sensors - which decrease their impedance when a force is applied.

These sensors are usually installed in the sole of the feet of the robots to measure reaction forces from the ground directly acting on the foot. Because of their convenient price and size, FSR are used in several solutions for sensing the CoP, particularly for mini-bipeds like Darwin-OP. However, FSR have some disadvantages. First, they are incapable of measuring forces acting in axes different than the surface normal. Second, a planar contact area must
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be ensured in order to obtain a reliable measure. Third, FSR can have issues with repeatability and “creep” during operation. This can be partly addressed by starting each experiment with a “warm up” consisting of repeated application of a force within the operative range prior to use. Also, FSR are generally nonlinear, and the level of error when measuring low forces is significantly higher. Despite of all this, FSR sensors can provide acceptable measurements if their constraints are met.

![DarwIn-OP FSR-Embedded Foot](image)

**Fig. 6. DarwIn-OP FSR-Embedded Foot. Price USD $449.90. Weight 0.1kg. Dim. 66x102x15 mm**

1.4.3 Alternative methods

References [4] and [8-10] present different solutions to sense the CoP. A compromise between size, weight, accuracy and cost is present in all solutions. In [4], conductive film is used in the sole of the foot to measure the field of forces. Small force sensors are used in [8] in special shoes to record ZMP trajectories of a human walking. In [9] H-slit Beam plates are installed as soles and the CoP is calculated by the level of unidirectional deformation of the plates.

A more complex system is implemented in [10] in order to deal with uneven surfaces. In this case, a system of photo sensors installed in the feet senses information about the unevenness of the ground. Based on this, the landing trajectory of the foot is changed to ensure 3-points of contact. Experiments were carried out using the robot WABIAN-2R. The weight of the foot with the sensing system was 1.5 Kg.

Our proposed method uses the deflection of its plastic toes to measure the force applied on them, and calculates the resultant CoP from those forces. The use of magnets and hall effect
1 Introduction

sensors yields to a low cost and reliable solution. Also, the size of the sensors and the material of the toes are very light.

1.5 Motivation of the present work

The research in [10] opens the discussion to a new context. What happens if the robot is not stepping on flat terrain?

The equality of CoP and ZMP holds for uneven terrains with the definition of a “virtual surface” [2]. The ZMP criterion holds for flat and non-flat terrain. One of the requirements for the correct functionality of the FSR sensors is a flat contact area, but flat soles in uneven terrains have a poor contact, decreasing the net area of the support polygon and therefore the range of stability.

As a possible solution, our new 3-toe foot (figure 4) has a different geometry and a new method to measure the CoP with the intention of maintaining an acceptable support polygon area, and ensuring correct measurement of the CoP on uneven surfaces.

Several things motivate the design and implementation of this new method to obtain the CoP in biped robots. First is the importance of the calculation of the CoP for ensuring stable walking gaits. Second is the need of a low cost, reliable and accurate solution for sensing forces and torques in the foot of biped robots. Third is the necessity of a simpler system capable of measuring CoP not only on flat terrains, but also when stepping on uneven surfaces.

In the next chapter our new foot and a new method for sensing the CoP will be described and analyzed. The goal is to obtain the same level of accuracy and low cost as standard FSR sensors but extending the capability to measure not only normal forces and tilting torques but also twisting torques even in non-flat terrains.
2 Design of the 3-toe Foot

Summary. In this chapter the design of a 3-Toe foot for sensing the CoP is presented. First, the justification for the geometry of the foot is explained. Then, the method for measuring the level of deflection of its toes is shown. Finally, the elements of the system are described, including all hardware and software components.

2.1 A 3-Toe foot

Even robots with vision capabilities, able to decide the most convenient point to step on, will end up dealing with small unevenness in the floor if working in real-world environments [10]. This “undetectable” unevenness, which could be of the order of centimeters, could be enough to make a robot with flat rigid feet to lose stability. The reason for this effect is unevenness in shape of the support polygon.

Consider the case in which the robot steps on a pyramidal unevenness in the floor with its left foot. If the point of contact between the pyramid and the sole is located in the center of the foot, the robot would measure the CoP of its left foot as safely posed in the center and therefore it would try to perform another step with its right foot. While the robot would assume its support polygon equal to the sole of its left foot, it would really be a single point. Obviously, trying to support the robot on a single point would bring instability.

The solution in [10] was to measure the unevenness in the floor and try to re-plan the landing of the foot accordingly. Another simpler alternative, instead of changing the motion, could be to try to reduce the probability of hitting an unevenness while having at least 3 points of contact between the foot and the floor. Three is the minimum number of points required to represent a plane. Clearance between the toes enables them to all make contact for a broad range of uneven and curved surfaces.

After deciding to design the foot with 3 toes, it is required to measure the normal forces acting on every toe to calculate the CoP. The popular FSR sensors are not a good option in this case, since they require a flat contact surface to work properly. Placing force sensors in the tip of the toes would only work if the point of contact is effectively located in the tip, and depending on the form of the unevenness and the angle of elevation of the toes, it may not be always the case.
2 Design of the 3-toe Foot

Instead of measuring the force in the tip of the toes, one could measure the level of deflection of the toes in the presence of force. Although linearity is not ensured, the level of deflection should be monotonically increasing with increasing force. Two intuitive points to measure the level of deflection would be a) the point where each toe is attached to the body of the robot, or b) the tip of the toe with respect to a reference point. Depending on the material, part of the displacement of the point of contact due to forces could be absorbed across the length of the toe, losing part of the information. Therefore, measuring the displacement of the tip of each toe with respect to a reference point would be more appropriate.

Figure 7 shows the design of the proposed 3-toe foot, with a circuit board coupled over it, where the sensors for measuring the deflection of each toe are located (reference points).

Fig. 7. The 3-Toe foot (left), and detail of a toe (right)

With the design shown in figure 7, the probability of contact with an unevenness is reduced. Even for rough or curved surfaces, there will exist 3 points of contact, unless an obstacle hits the foot in the center. In order to touch the center of the foot the unevenness must be significantly tall and narrow. Although the points with highest probability of contact with the ground are the tips, any point of the toe tip could be a point of contact depending on the
Design of the 3-toe Foot

geometry of the unevenness. However, the design allow us to measure the CoP also under that circumstance.

The material and thickness of the foot will determine the level of deflection under a given force. Therefore, the type of the material and size of the toe supports should take in account the weight of the biped. In this prototype, the length of the toes make the sensors location coincide with the boundaries of the Darwin-OP foot. The material is ABS plastic and the toe support dimensions were determined heuristically.

2.2 Sensing Toe deflection

In order to measure the deflection of the toes, magnets have been installed in their tips. Variations in the relative position of the magnet with respect to the reference point (in the circuit board) will generate changes in the magnetic field. A set of hall effect sensors are installed in the board forming a triangle. The aim is to measure the position in x,y,z of the magnet, and then extract the level of force and torque applied over the toe from its relative location. Figure 7 illustrates the detail of the magnet and the arrangement of Hall Effect sensors in one of the toes of the foot.

The Z axis is defined parallel to the line that connects the centroid of both the magnet and the arrangement of sensors. Variations in the Z axis should reflect changes in the level of force normal to the plane of the foot (i.e. the plane of the circuit board and reference points). It could be desirable to measure changes of the position in other axes as well, since those changes should provide information regarding torques acting on the foot. That is the reason for the non-aligned location of the sensors.

2.3 Description of the system components

The prototype has been integrated with the Geometrical and Physical Computing Laboratory (GPC) biped Robot (figure 1). This apparatus uses Robotis Dynamixel® servos for controlling the motion of its limbs. The Dynamixel servos use a proprietary communication protocol transported over a serial RS-485 bus. The communication is meant to handle the exchange of data packets between a master and a set of slaves. The master is the main
processor of the system and the slaves are the sensors and actuators. Therefore the foot, acting as a sensing system, must be able to communicate via the Dynamixel® protocol.

### 2.3.1 Microcontroller Module

We use a Microcontroller module to implement the communication protocol and also to process the information from the Hall effect sensors. Given the limitations of space and the need for a serial RS-485 interface, a Crumb644 V1.1 module from Chip45 has been installed. The module includes an Atmega644PA micro controller, 32 I/O ports, and a RS-485 transceiver. The module has been installed with a power regulator Power S-501 V1.0 (also from Chip45), which converts the 12VDC input of the Dynamixel® bus to 5VDC for feeding the controller and sensors.

![Fig. 8. Detail of the 3-Toe foot with the Crumb644 (top) and the power regulator (Right)](image)

### 2.3.2 Hall Effect Sensors

The sensors used in the prototype are The Allegro® A1356 Hall effect sensors. These are high precision linear sensors with an open drain pulse width modulated (PWM) output. The
2 Design of the 3-toe Foot

PWM output has strong noise rejection, and is convenient given the capabilities of most Microcontroller units to detect changes in digital inputs. The A1356 come in a conveniently small SIP package, and it requires only three connections: VCC, Ground, and Signal Output.

In order to ensure that the sensors will maintain their positions and relative distances they have been mounted over a circular plastic container and then soldered to the board. No extra circuitry is required since the open drain output of the sensors is directly coupled with the configurable Pullup resistors of the I/O ports of the microcontroller.

2.3.3 Printed Circuit Board

Printed Circuit Boards (PCB) were designed separately for the right and left foot. Figure 9 depicts the PCBs. The purpose of the holes in the center of the boards is to allow the pass of screws to connect the foot with the legs of the robot. Surface-mounted capacitors are used to filter the noise coming from the power supply. Each board’s size is 53x88 mm.

![Fig. 9. Printed Circuit Boards designed for the prototype](image-url)
2 Design of the 3-toe Foot

2.3.4 Software components

An algorithm has been deployed to handle the communication protocol, and to convert the PWM pulses from the sensors into numeric values. The algorithm runs in the Atmel ATMEGA644PA microcontroller in the Crumb644 board. The system does not perform calculations regarding the location of the CoP. It merely delivers the values of the pulse widths in microseconds. The computation of the CoP will take place in the main processor of the robot. The algorithm can be summarized in the following procedure:

**Main Program**

1. **Begin Initialize**  
   table=default, input-buffer=0, output-buffer=0, i=0
2. **Do**  
   Count pulse width on Input i
3. Store input i in table position start+i
4. increment i
5. **If** i =9
6. i=0  
7. **end**
8. **If** new_serial_packet_arrived
9. **Goto** process_serial_request  
10. **end**
11. **While** 1

**process_serial_request**

1. **While** packet_incomplete
2. wait
3. **end**
4. **If** Is_request || Is_ping
5. **If** Slave_ID=Foot_ID
6. get_checksum_result
7. Send_table_values + checksum_result
8. **end**
9. **end**

Although the calculation of the CoP is not present in this algorithm, it will be shown in chapter 3 that, after investigating the correct mathematical transformation, the calculation of the CoP becomes trivial, and can be included in the code. The process to find the transformation to get the CoP from the pulse widths of the PWM signals of the sensors will be also described in chapter 3.
3 Calculating the CoP

Summary. In this chapter, the empirical behavior of the proposed system is shown. Initial experiments demonstrate the viability of obtaining the 3-D location of the magnet with respect to the sensors from the measures of the magnetic field. Analysis of collected data will suggest a first approach for calculating the CoP. Several approaches for obtaining the CoP are presented and compared.

3.1 Obtaining magnet location from the magnetic field measurements

As discussed previously, the aim is to obtain the information regarding the forces and torques applied to each toe, which we assume correlated with the position of the magnet located in the tip of each toe, and therefore correlated with the magnetic field in the reference point. To confirm these assumptions, two different tests have been performed: the first one is to observe the behavior of the magnetic field with respect to 1-dimensional displacement of the magnets, and the second uses a 2-dimensional swipe (figure 10b). The results of the 1-D test are shown below in figure 10a.

![Figure 10a](image)

**Fig. 10a.** Sensor’s pulse width as a function of distance to the magnet in the Z axis. 1D swipe

From figure 10a it is clear that, although linearity is not ensured, the pulse width of the signal from the sensors decreases in relation to the distance to the magnet in the Z-plane.
3 Calculating the CoP

In order to obtain torques in the plane of the circuit board, we need to be able to detect motions in the X-axis. To confirm that motions in x are detectable, a 2-D swipe was performed. The measurements of the pulse width in the X-Z plane are shown in figure 11.

Some data manipulation is required in order to see the desired Input-Output relationship. First, the pulse width data is reflected with respect to the x-z plane.
3 Calculating the CoP

Finally, by choosing the maximum among the 3 sensor's inverted pulse width, we obtain a model which follows the actual motion. Figure 13 shows the resulting data distribution, along with the real distribution of the distance as a function of x,z. It can be concluded, based on the graphs, that the information of the magnet's location in x-z is contained in the pulse width of the cluster of sensors.

![Figure 13. Maximum reflected pulse width (left), and actual distance between the magnet and the sensors in the x-z plane during the experiment (right).](image)

The location of the toe tips in the x-z plane can be obtained from the sensors. Now, it is required to confirm that, from the location of the toes, we can extract the applied forces and torques, and therefore, the CoP.

3.2 Approaches for obtaining the CoP from sensor data

In this work, the problem of obtaining the CoP from the sensor's data has been treated as a function fitting problem. The aim is to obtain a bi-dimensional output \( (x,y) \), which would indicate the location of the CoP point \( p \) with respect to a reference point located in the “heel” of the foot. As seen in figure 14, the range for \( x \) will be \( 0 \leq x \leq 53 \) mm, whereas the range of \( y \) will be \( 0 \leq y \leq 88 \) mm. Also, the CoP location must be inside the triangle formed by the centers of the 3 clusters of sensors, which can be expressed as a third constraint \( y \geq 1.66x \).
3 Calculating the CoP

The inputs will be the data from the 9 sensors of the foot. A CoP will be calculated for each foot, and the CoP of the robot will be computed as a weighted average of these when in double support.

![Coordinate system](image)

Fig. 14. Coordinate system used to represent the CoP location on each foot.

3.2.1 Weighted Average of Maximum pulse width

The first approach, based on the results of the experiment in section I, should be to try to obtain the CoP using as input the maximum of the inverse of the sensor’s pulse width. One way to simplify the problem is to turn around the magnet, generating an opposite polarity in the magnetic field. That change is equivalent to invert the value of the pulse width. This change reduces the input to be the maximum of the sensor's pulse width.

If one has the values of the force in each of the 3 toes, the CoP is calculated as the weighted average of the vectors representing the 3 points. Therefore, it would be convenient to use this information to model the structure of the transformation function. The results of the 2-D swipe of the magnet suggest that the maximum pulse width represents the distance between the magnet and the sensors, which we assume correlated with the force. Yet, the constant of proportionality (which we will call $w$) for each pulse is unknown.
3 Calculating the CoP

The weighted average on maximum pulse width approach consists in finding the values of the weights $w_kx$, $w_ky$ for $k=1,2,3$, $Cx$ and $Cy$ which correctly converts our pulse widths to the real CoP. Figure 15 depicts the structure of the function and the unknown variables $w$ and $C$. In other words, the CoP is calculated as the weighted average of the scaled inputs, which are the maximum value of the 3 sensors on each cluster.

![Diagram](image)

Fig. 15. Scheme of the Weighted Average on Maximum pulse width approach to find the coordinates $x,y$ of the CoP

3.2.2 Weighted Average of Mean pulse width

Although from the 2-D swipe we have seen the the maximum value seem to better represent the distance magnet-sensors, it may be worth to try other approaches. Selecting the maximum value can be a undesirable, since it is very sensitive to noise. An alternative to this problem is to compute the mean of the pulse width of the 3 sensors of each cluster, and use that value as the input to calculate the CoP. The mean acts as a low-pass filter, making the measures less sensitive to noise.

Again, the goal is to obtain the value of the scale factors that better reproduces the CoP from the inputs. Figure 16 shows the model proposed. The fitting function problem has in this case 3 inputs, 8 parameters and 2 outputs.
3 Calculating the CoP

3.2.3 Single Layer Artificial neural Network

In order to explore alternative solutions to the function fitting problem, a one-layer Artificial Neural Network (ANN) is presented. ANN’s have shown positive results in fitting linear and nonlinear models, and their computational cost is low. In this case, no previous knowledge of the system is assumed, and the inputs are not pre-processed. All pulse widths are set as inputs to a single layer ANN, and linear activation functions deliver the outputs \( x \) and \( y \).

![Diagram of Single Layer Artificial Neural Network](image-url)
3 Calculating the CoP

3.2.4 Sensor Average Artificial neural Network

In order to reduce the number of parameters $w$ in the ANN approach, the number of inputs can be reduced. This can be done by using the average of the inputs per cluster as inputs to a simpler single layer ANN. This would reduce the computation of the CoP, as well as the complexity of the model. Figure 18 shows the proposed variation of the ANN approach. The number of parameters become just 8, instead of the 20 of the previous model.

![Diagram of Sensor's Average Artificial Neural Network](image)

Fig. 18. Sensor's Average Artificial Neural Network approach to find the coordinates $x, y$ of the CoP

3.2.5 Modified sensor average Artificial Neural Network

Finally, a second variation of the ANN approach is presented. In order to add nonlinearity to the model, the squared means of the clusters are included as inputs to the ANN. Increasing the dimensionality of the data input is frequently used in supervised learning algorithms (support vector machines) to find linear solutions in higher-dimensional spaces to nonlinear problems. This solution requires 14 parameters, and the model has 6 inputs and 2 outputs.
3.2.6 Learning model parameters

In all cases, a set of real input-output pairs will be used as training data to estimate the parameters. The inputs will be collected directly from the sensors, whereas the outputs will come from a UFS sensor, which would act as out ground truth. In chapter 4, The experiment setup will be presented. Also, the average error of each approach will be calculated with respect to the ground truth.
4 Experimental Results

Summary. In this chapter, a set of experiments are run to validate the models proposed in chapter 3, and performance of each model is measured by comparing its output respect to data from an industrial load cell. The most accurate method is then chosen to obtain the CoP. The experiments also prove the functionality of the system, by comparing its results with the DarwIn-OP FSR-Embedded sensors.

4.1 Experiment Setup.

Input-Output pairs are required to calculate the parameters of the models described in chapter 3. The 3-Toe foot provide the measures of the positive pulse width of the PWM signals from the sensors (inputs). An industrial load cell is used to collect the outputs, which are the coordinates \( x \) and \( y \) of the CoP. The load cell is coupled to the 3-Toe foot using plastic couplers, avoiding the need of changing other pieces in the leg of the robot.

Fig. 20. 3-toe foot assembled to a Load Cell. Mounting for running the experiment in the RPBP robot
4 Experimental Results

The RPBP robot is used to apply forces in the foot, changing the location of the CoP in a defined sequence. This is accomplished by attaching the robot to a rigid point from the upper side. Then, the robot is programmed to move its leg towards the floor, generating an initial load over the foot. Posterior tuning is performed to ensure that the CoP is located in the center of the load cell $p_l$. A sequence of small variations of the position of each motor of the leg are then executed, moving the CoP in the foot in all directions. Pulse widths and CoP locations are stored in a table. The experiment was repeated 8 times.

Fig. 21. RPBP robot and CoP location during the experiment 7

4.2 Errors of the different approaches

Using an Evolutionary Algorithm [11], the parameters for the 5 different models were obtained, trying to minimize the squared error with respect to the ground truth provided by the load cell. The dataset of experiment 4 was used to calculate the parameters in all cases. The remaining 7 datasets were used to validate the models. The experiment was also executed using the Darwin-OP FSR-Embedded sensors, with the purpose of comparing the accuracy of our models with respect to commercial systems.

The mean error from the 5 methods, calculated over the 8 datasets, are shown in the table 1. The Darwin Foot average error shown in table 1 was calculated by running the same
4 Experimental Results

experiment 5 times with the robot using the Darwin foot, and then calculating the error respect to the Load Cell values.

<table>
<thead>
<tr>
<th>TECHNIQUE</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Average</th>
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<tbody>
<tr>
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<td>3.68</td>
<td>3.91</td>
<td>5.9</td>
<td>2.97</td>
<td>3.26</td>
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<tr>
<td>Weighted average on mean pulse width</td>
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<td>3.71</td>
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<td>5.93</td>
<td>2.79</td>
<td>3.28</td>
<td>3.2</td>
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<td>6.73</td>
<td>6.1</td>
<td>8.01</td>
<td>4.8</td>
<td>5.43</td>
<td>4.98</td>
<td>5.85</td>
<td>5.99</td>
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<td>6.8</td>
<td>6.5</td>
<td>5.4</td>
<td>6.7</td>
<td>5.9</td>
<td>6.1</td>
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<td>Darwin Foot Average Error</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.43</td>
</tr>
</tbody>
</table>

Table 1. Mean error in millimeters for all approaches, in 8 data sets.

The average error of the 3-Toe foot is of the same order of the Darwin-OP FSR-Embedded sensors in all cases. Although the minimum average error is obtained using the weighted average of the maximum pulse width, the weighted average on mean pulse width has been selected to be implemented in the foot given its better behavior in presence of noise. Table 2 presents detailed information about the experiments.

<table>
<thead>
<tr>
<th>EXPERIMENTS INFORMATION</th>
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<tr>
<td>Experiment</td>
</tr>
<tr>
<td>Date</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Points stored</td>
</tr>
</tbody>
</table>

Table 2. Experiments information.

4.3 3-Toe foot measuring the CoP

The location of the CoP given by the 3-Toe foot using the weighted average on mean pulse width, along with the value of the error for each point with respect to the load cell measurement, are shown in figure 22 for experiments 5 and 6. In both cases, around 90% of the CoP locations given by the 3-Toe foot had a difference of less than 6 millimeters with respect to the ground truth. A circle of radius 6 mm (where 90% of the points are, with respect to the ground truth) corresponds to 4.2% of the area of the support polygon of the 3-Toe foot.

The average error in the 3-Toe foot, when the applied force is equal or greater than 16 Newtons (which corresponds to the weight of the robot), is around 2.5 mm. This is because bigger forces produce bigger deflection of the toes, which makes the changes in the
magnetic field bigger. The variation in the error in different experiments may be caused by small changes in the initial position of the magnets respect to the board.

Fig. 22a. CoP location in $(x,y)$ and error distribution in $z$ mm for 3-Toe foot in experiment 5

Fig. 22b. CoP location in $(x,y)$ and error distribution in $z$ (mm) for 3-Toe foot in experiment 6

The plot of the error distribution of the DarwIn-OP FSR-Embedded sensor is presented in figure 23. The area where the CoP can be located in the case of the DarwIn foot is rectangular. It is also visible that the FSR sensors hav problems calculating the CoP near the
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edges. In those cases, the contact between the sensors located in the opposite side of the foot and the floor is not good enough to produce a valid measurement. This phenomena also affects the behavior of the 3-Toe foot.

Fig. 23. CoP location in (x,y) and error distribution in z (mm) for Darwin-OP foot
Conclusions

This thesis presented a 3-Toe foot for measuring the CoP. Experimental results demonstrate that the 3-Toe foot is a reliable, low-cost solution for sensing the CoP in bipeds. The geometry of the foot allows the calculation of the CoP in flat and uneven surfaces. The sensitivity, repeatability and reliability of the 3-Toe foot is comparable with the characteristics observed in the DarwIn-OP FSR-Embedded sensor. The cost of the the 3-Toe foot is, however, significantly lower.

Although some simple models were presented and tested for transforming the data from sensors to CoP coordinates, other models can be further explored to reduce the error. Also, further analysis of the influence of the geometry, thickness and composition of the foot in the sensitivity of the sensing system is required.

Short term future work includes the implementation of stable gait algorithms on the RPBP robot using the CoP provided by the 3-Toe foot, in both flat and uneven terrain.
Bibliography


Bibliography