Design of a Golf Putting Pneumatic Mechanism Integer *vs* Fractional Order *PID*

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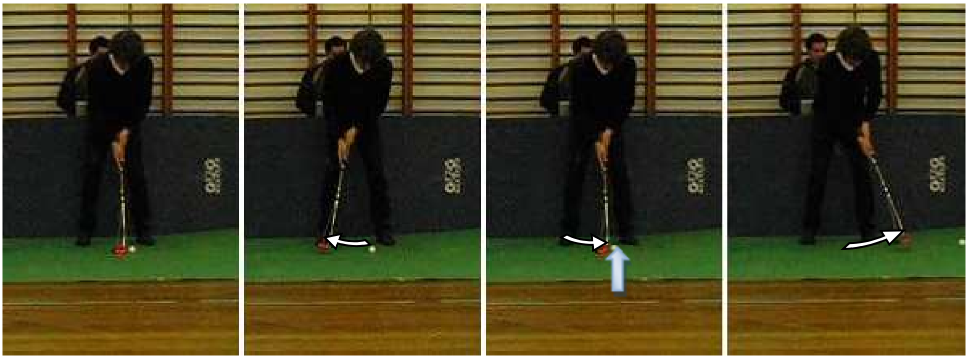
1. Introduction

According to Dave Pelz, one of the foremost short game and putting instructors in golf, the putting technique, or simply the putt, is defined as a light golf stroke made on the putting green in an effort to place the ball into the hole (Pelz, 2000). Hence, the putt is used in short distance shots on or near the green, as seen in Fig. 1. Similarly, putter may refer to a golf club used in the putting stroke.

The golf putting is an important aspect of golf because it can greatly affect a player's game performance and overall score. In the last years, an increasing number of researchers have been studying this gesture in order to understand its biomechanical characteristics (Pelz, 2000; Hume et al., 2005). However, the relative importance of the phases that describes the putt (Fig. 1) shows some inconsistencies (Pelz & Mastroni, 1989; Pelz, 2000).



a) b) c) d)

Fig. 1. Phases of the putting: a) Initial stage; b) Backswing; c) Downswing and ball impact; d) Follow-through.

For instance, most golf experts consider that the key to a successful putt is in the power of the follow-through (Pelz, 2000). For instance, James Braid (1907), five time winner of *The Open Championship*, highlights this viewpoint by saying that "*the success of the drive is not only made by what has gone before, but it is also due largely to the course taken by the club after the ball has been hit*". However, the importance of the follow-through may be only an indication that the first part of the stroke (*i.e.*, backswing and downswing) was well played.

Also, it is not clear if the vertical trajectory of the putter is relevant for the success of the putting. Being a pendulum-like movement it is known that when the putter reaches the ball (*i.e.*, angle of inclination of the putter near 90 degrees) the vertical velocity is zero or near zero. Instead of using a regular putter, can we say that we could obtain the same performance if applying the exact same force on the golf ball using, for instance, a snooker cue?

To fill the niche area which lies between classical engineering and sports science, researchers has been exploring a recently emerged field denoted as sports engineering. The main purpose behind this new field is to apply engineering principles to understand, modify or control human biological systems directly or indirectly involved in activities related with sports, designing and producing auxiliary tools, such as monitoring, diagnosis and training of the athlete.

Thus, in this book chapter, a novel testbed for evaluation of the golf putting is proposed. The developed putting mechanism consists on a pneumatic system that emulates the golf putting based on real reference data of expert golf players previously studied in (Dias et al., 2010). All the reference data was retrieved using a detection technique to track the putter's head and an estimation technique to obtain the kinematical model of each trial which was further explained in (Couceiro et al., 2010a).

Though pneumatic actuators are often employed in industrial automation for reasons related to their good power/weight ratio, easy maintenance and assembly operations, clean operating conditions and low cost, it is not easy to control them, due to the nonlinearities. The presence of the air along with its natural compressibility introduces complexities such as friction forces, losses and time delays in the cylinder and transmission lines (Richer & Hurmuzlu, 2001).

The pneumatic servo-system is a very nonlinear, time-variant, control system because of the compressibility of air, the friction forces between the piston and the cylinder, air mass flow rate through the servo-valve and many other effects caused by the high nonlinearity of pneumatic systems. Furthermore recent improvements of digital technologies have opened new scenarios about pneumatic systems. In particular the use of the Pulse Width Modulation (*PWM*) technique is particularly attractive considering the possible use of cheap on/off valves driven by a *PWM*.

Nevertheless, the complexity of designing a controller for a system involving a complex dynamic behaviour such as a pneumatic actuator needs to be robust and efficient (Shen et al., 2006). To that end, both integer and fractional order Proportional-Integral-Derivative (*PID*) controllers will be studied and implemented on the open-source electronics prototyping platform *Arduino* which will be used to control the pneumatic device.

The controllers' gains will be obtained using the Particle Swarm Optimization (*PSO*) technique in order to achieve the minimum Integral Time Absolute Error (*ITAE*) when the pneumatic putter follows a desired trajectory. The optimization process will be accomplished using a *MatLab* script that iteratively calculates the *ITAE* between the desired putter's trajectory sent to the *Arduino* board over *USB* and the real trajectory performed by the pneumatic putter sent back from the *Arduino* board to the computer.

Bearing these ideas in mind, this book chapter is organized as follows. Section 2 presents the state-of-the-art of several experimental devices used in sport context while the proposed golf putting mechanism based on a pneumatic cylinder is described in section 3. The control architecture and optimization methodology is presented in section 4. Section 5 presents the evaluation of the putting mechanism. Section 6 outlines the main conclusions.

2. Related work

In the last few years, several devices have been developed to improve athlete's performance and to reveal particular features of a given sport. Many sport such as tennis (Salansky, 1994), table tennis (Lu, 1996) and baseball (Rizzo & Rizzo, 2001) were the first ones having their own training machine. However, more recently, many other sports had benefited from such devices.

Therefore, this section presents a selection of several mechanisms used in sport context mainly focusing on the design and controller characteristics. Furthermore, the state-of-the-art of experimental devices used to replicate the putting is thoroughly presented and discussed.

2.1 Sport devices

Similarly to tennis, badminton requires a high level of footwork and speed. One of the training machines used in badminton is called the Automatic shuttle feeder (*ASF*) (Kjeldsen, 2009). *ASF* can feed all over the court fulfilling the technical training as well as the physical and reaction training. As the presented work, *ASF*'s uses compressed air, thus requiring an external compressor to supply compressor air for the machine.

Nevertheless, just like in tennis, spring-like strategies have also been explored in badminton (Yousif & Kok, 2011). The springs are the source of the force which is controlled by an AT89S51 microcontroller. However, just like most high-speed shooting mechanisms, controller strategies are not considered and basically consist on a common launcher.

The development of a cricket bowling machine is presented in (Roy et al., 2006). The machine transfers the kinetic energy to the ball by frictional gripping between two rotating wheels whose speed is controlled by varying the analog voltages generated through a micro-controller 89C51 and associated peripherals. The authors claim that the machine is portable and low cost. However, it weights around 34Kg having 2 meters height with a cost of approximately 1200€.

The authors in (Kasaei et al., 2010) present a solenoid based multi power kicking system that enables loop and varies shooting power. The device takes use of a solenoid system to control the shooting power applying Pulse Width Modulation (*PWM*) on the pulse source in the control circuit. However, experimental results do not depict the precision or accuracy of the shooting mechanism.

Actually, devices that recreate high-speed or high-power shooting mechanism lacks on precision and accuracy since researchers have paid little or no attention to control architectures. However, slower gestures, such as the putting, have been objects of study in the fields of robotics and sports engineering, thus highlighting control techniques, sensory systems and ecological validity.

2.2 Putting devices

This section presents the state-of-the-art of experimental devices that were used to replicate the putting in field and laboratory context, *i.e.*, in real teaching and learning situations. Therefore, several papers are presented focusing the area of robotics in agreement with some assumptions underlying the systems of human movement, which studied the putting through the implementation of robotic arms and other mechanisms. In addition, as a multidisciplinary approach, this section aims to describe the advantages and disadvantages of these devices when compared to the one proposed in this paper, thus highlighting their contribution, while maintaining the scientific validity of the ecological execution of the putting.

Analysing the literature, Webster and Wei (1992) presented a robot vision golfing system *ARNIE P* (Automated Robotic Navigational unit with Intelligent Eye and Putter) that uses a *3D* tracking system to analyze the putting in the laboratory context. The presented mechanism is described by a good hand-eye coordination and intelligent sensor feedback. The robot is able to store and retain the location of the ball from two separate cameras during the time interval between the golf ball initially crossing a trigger scan line and the ball coming to a complete stop. Operationally, the robot used in this study presents a human-like gesture, taking into account that it can execute the movement while performing automatic tracking using *3D* acquisition software. However, its main limitation resides in the complexity inherent to robot programming in a cartesian coordinate motion to putt the ball effectively (swing the club). Furthermore, the use of such a complex system (*e.g.*, binocular stereo vision, robot arm motion, heuristic feedback, learning) is not fully effective to carry out the technical gesture, since this study essentially relies on artificial intelligence techniques and robotics, thus ignoring ecological validity. In addition, results are inconsistent with human performance, especially in terms of putting at shorter distances (Pelz, 1990, 2000).

Khansari-Zadeh and Billard (2011) developed an industrial robot with a mechanical arm with six *dof* denoted as Katana-T. Through the Stable Estimator of Dynamical Systems (*SEDS*) and using regression techniques, e.g., Gaussian Process Regression (*GPR*) or Gaussian Mixture Regression (*GMR*), it was possible to collect data on the robotic arm performance while executing the putting. From the kinematic point of view (*i.e.*, biomechanics of human movement), the main contributions of this work show that the putting is a complex task that is under the influence of different disorders that can be studied in various trajectories and ball positioning on the green. This aspect is reinforced by the same authors from a dynamical system perspective as an open phenomenon making an analogy with human movement system. The main limitation of this work refers to the *dof* of the robotic arm, which, despite its originality and innovation, has difficulties in representing a pendulum-like motion that characterizes the putting, far from featuring the ecological validity of this gesture. For instance, comparing with the work of Pelz (2000) which describes a robot with several *dof* that reflects almost perfectly the motor execution of a human being (*e.g.*, pendulum motion, putting amplitude, velocity and acceleration), the study of Khansari-Zadeh and Billard (2011) fails in successfully representing the task.

Another work presented by Jabson et al. (2008) developed a robot that autonomously moves using two *DC* motors controlled by a remote *PC* using fuzzy logic. The *Autonomous Golf Playing Micro Robot* is equipped with a servomotor used to execute the putting. The microcontroller is used to process the information sent by the computer through radio-frequency (*RF*) communication, thus controlling the motors. The robot is equipped with a camera allowing it to play golf while avoiding obstacles. The wheels are attached at the back and a ball caster at the center in order to achieve optimum stability. This work is particularly interesting because of the developed vision system that detects the position of the robot, golf hole, golf boundaries, and the golf ball within the playing field on real time using color object recognition algorithm. A modified golf tournament between autonomous robot golf player and man operated robot golf player was conducted. Results obtained in this study show the accuracy and robustness of the autonomous robot in performing such task. However, the micro robot has a limited putting representation, taking into account its size and the functions it performs.

More recently, Mackenzie and Evans (2010) described a robot that performs the putting using a high-speed camera (*TOMI* device). This was used to measure the putter head speed and impact spot of putts executed by a live golfer. The authors stated that the putting robot generated identical putting strokes with known stroke paths and face angles at impact. This work allows the kinematical analysis of the putting and the influence of key kinematic errors. However, the authors do not go beyond the biomechanical analysis, which limits their scientific approach when compared to similar experimental devices.

For instance, researchers such as Linda and Crick (2003) presented an autonomous robot which includes a *PID* feedback control system associated to a wireless communication mechanism. This robot autonomously performs the putting using a digital control system to establish the pose of the robot. It is noteworthy that the inclusion of a *PID* control with shaft encoder sensors is a novel feature of this work. However, it is also true that the system "heavy" and complex in terms of information processing and synchronization of the several components.

Finally, Munasinghe, Lee, Usui and Egashira (2004) described a telerobotic testbed via a mechanical arm. A user-friendly operator interface and Synchronized Orientation Control (*SOC*) with multiple commands are one of the most innovative aspects of this study. A laser pointer is used to help remote operator in perceiving self-location and navigation, whereas orientation control has been completely automated and synchronized to the position commands of the teleoperator. This device is important to putting kinematical analysis, taking into account that it is very accurate. However, its main limitation is evident since this device offers small information about the process variables of motor execution (*e.g.*, putting amplitude, speed and acceleration).

The following section presents the development of a pneumatic putting mechanism that will further be compared to real data obtained by real expert golf players.

3. Experimental setup

We emphasize that the focus of this work will not be directly related with the analysis of the phases of the putting motion presented in Fig. 1 (*e.g.*, backswing, downswing, ball impact and follow-through) (Pelz, 2000). However, the proposed mechanism will allow reproducing the phases of the horizontal component of the putting.

The putting mechanism consists on a pneumatic actuator CE1B32-200 equipped with a putter's head from a Putter Jumbo Black Beauty (Fig. 2). As an important driving element, the pneumatic cylinder is widely used in industrial applications for many automation purposes thanks to their variety of advantages.

The schematic of the putting mechanism is depicted in Fig. 3. The system consists of air supply, pneumatic cylinder (SC) with encoder (CE), pressure sensors (P_X), limit switches (FC_X), electro-valves (VC_X), Interface board (IB) and a *Arduino* board (µC) (which consists of an 8-bit microcontroller with A/D and D/A converters, external interrupts and other features) connected to a main computer, $x = \{1, 2\}$.

The scale cylinder (SC) is equipped with two electro-pneumatic proportional valves VER2000-03F (VC_1 e VC_2) which allows controlling the piston position with a Pulse Width Modulation (*PWM*) current signal used to represent an analog current value. VC_1 controls the cylinder to move forward (*i.e.*, downswing, ball impact and follow-through) while VC_2 controls the cylinder to move backward (*i.e.*, backswing).

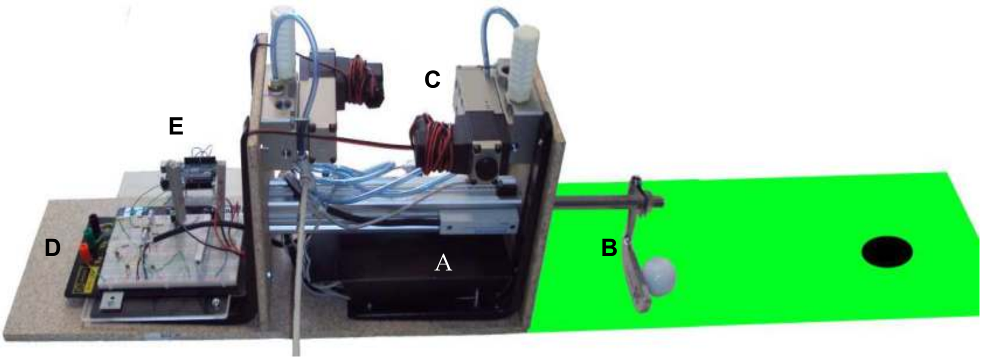


Fig. 2. Putting Mechanism: A - High Precision Scale Cylinder CE1B32-200 with encoder;
B - Putter's head from Putter Jumbo Black Beauty; C - Electro-Valves VER2000-03F;
D - Interface Board; E - *Arduino* Control Board.

As an important driving element, the pneumatic cylinder is widely used in industrial applications for many automation purposes thanks to their variety of advantages. In fact it is simple and clean, has low cost, high speed, high power to weight ratio, it is easy to maintain and has inherently compliance.

The schematic representation of the Interface board (IB) from Fig. 3 shows that the *PWM* current signal from the Interface board is proportional to the *PWM* voltage signal from the *Arduino* board (µC). A voltage value between 0v and 5v from the *Arduino* corresponds to a current value between 0A and 1A from the Interface board.

The duty cycle of the *PWM* voltage signal of the *Arduino* board (μC) will be the controller output $u(t)$ while the error $e(t)$ will be the difference between the reference trajectory (*i.e.*, controller input) sent by the computer and the real trajectory of the pneumatic putter provided by the encoder (CE).

The encoder *MODEL CE1 from MONOSASHI-KUN* have a resolution of 0.1mm/impulse, an accuracy of ± 0.05mm, with an open collector output of 12V of two impulses 90 degrees out of phase. This is an incremental rotary encoder with a magnetic resistance element which function is to provide the relative position of the piston rod (Fig. 4).

When the sensor passes through the magnetic section, it presents an output described by a 2-phase signal of sine and cosine by the piston rod movement. For this waveform, 1 pitch (0.8 mm) is equal to one cycle. This signal is then amplified and divided into 1/8. As a result, 90 degrees phase difference pulse signal is output. This signal is represented by two impulses (phase A and phase B) and works like an ordinary incremental rotary encoder (quadrature encoder).

Since the output of the encoder has a logical high level of 12v voltage, the Interface board (IB) is once again used to convert this signal to a standard Transistor–Transistor Logic (*TTL*) of 5v to be compatible with the external interrupts of the *Arduino* board (μC).

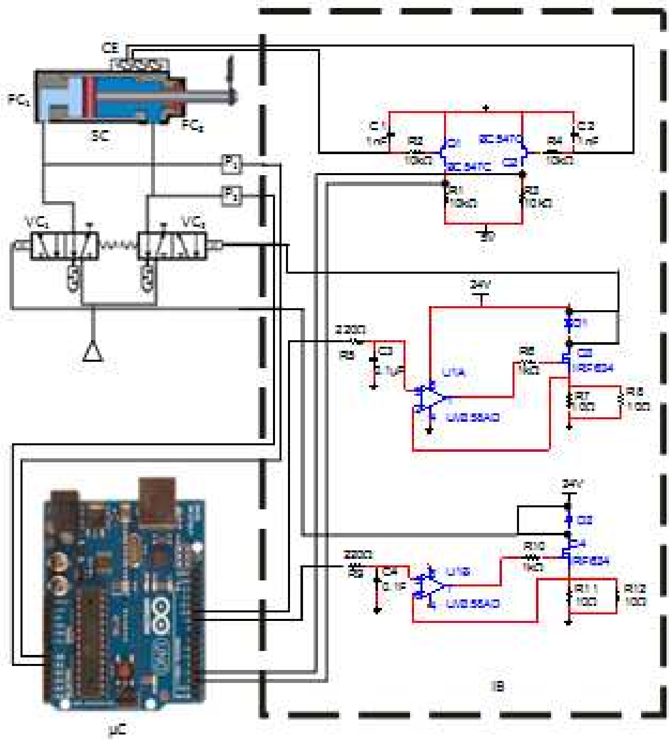


Fig. 3. Schematic of the Putting Mechanism.

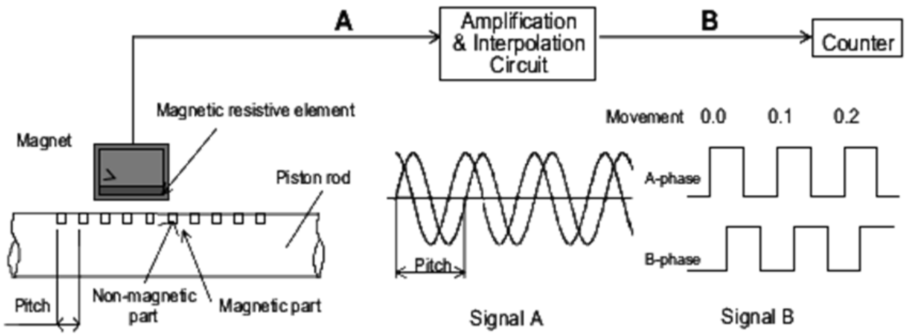


Fig. 4. Feedback System using encoders.

The hardware specifications of the developed putting mechanism are summarized in Table 1.

Action	*Double acting single rod (non-rotating piston)*
Fluid	*Air*
Operating pressure	*0.15MPa {1.5kgf/cm²} to 1.0MPa {10.2kgf/cm²}*
Maximum Putting speed	*3000 mm.s⁻¹*
Power supply	*24V DC (±10%) (Power supply ripple: 1% or less)*
Maximum Current consumption	*600 mA*
Encoder Resolution	*0.1mm/pulse ± 0.05mm*
Output signal	*A/B phase difference output*
Communication	*Serial RS-232*
Response time	*0.05 sec.*
Weight	*7 kg*
Dimensions (Length x Height x Width)	*634mm x 325mm x 258mm*

Table 1. Putting Mechanism Specifications.

Given the above, the proposed mechanism respects the ecological validity of putting performance with regard to the ball impact velocity which is very accurate. Furthermore, this mechanism allows executing consistent replications of the movement (Delay et al., 1997; Coello et al., 2000).

Therefore, this novel approach suggests that it will be possible to study the golf putting, thus revealing the mechanics of this gesture in field and laboratory context.

As next section shows, the proposed putting mechanism will benefit from fractional order controllers whose dynamic behavior is described thorough differential equations of non integer order.

4. Control architecture

Though pneumatic actuators are often employed in industrial automation for reasons related to their good power/weight ratio, easy maintenance and assembly operations, clean operating conditions and low cost, it is not easy to control them, due to the nonlinearities.

The presence of the air along with its natural compressibility introduces complexities such as friction forces, losses and time delays in the cylinder and transmission lines (Shearer, 1956; Richer & Hurmuzlu, 2001).

The pneumatic servo-system is a very nonlinear, time-variant, control system because of the compressibility of air, the friction forces between the piston and the cylinder, air mass flow rate through the servo-valve and many other effects caused by the high nonlinearity of pneumatic systems.

Furthermore recent improvements of digital technologies have opened new scenarios about pneumatic systems. In particular the use of the Pulse Width Modulation (*PWM*) technique is particularly attractive considering the possible use of cheap on/off valves driven by a *PWM*.

Nevertheless, the complexity of designing a controller for a system involving a complex dynamic behaviour such as a pneumatic actuator needs to be robust and efficient (Åström, 1980; Chien et al., 1993; Shen et al., 2006).

In this work, both classical (*aka*, integer order) and fractional order Proportional-Integral-Derivative (*PID*) controllers were compared while emulating the putting gesture in order to overcome the nonlinearities inherent to pneumatic systems.

4.1 Integer *PID* controller

In general, a classical *PID* controller, usually known as integer *PID* controller, takes as its inputs the error, or the difference, between the desired set point and the output. It then acts on the error such that a control output, u is generated. Gains K_p, K_i and K_d are the Proportional, Integral and Derivative gains used by the system to act on the error.

The Proportional Integral and Derivative PID control action can be expressed in time domain as:

$$u(t) = Ke(t) + \frac{K}{T_i}\int e(t)\,dt + KT_d\frac{de(t)}{dt} \tag{1}$$

Taking the Laplace transform yields:

$$G_c(s) = \frac{U(s)}{E(s)} = K\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{2}$$

4.2 Fractional *PID* controller

Fractional order controllers are algorithms whose dynamic behaviour is described thorough differential equations of non integer order. Contrary to the classical *PID*, where we have three gains to adjust, the fractional *PID* (*aka*, $PI^{\lambda}D^{\mu}$) has five tuning parameters, including the derivative and the integral orders to improve de design flexibility (Couceiro et al., 2010c).

The mathematical definition of a derivative of fractional order a has been the subject of several different approaches. The Grünwald-Letnikov definition is perhaps the best suited for designing directly discrete time algorithms.

$$D^{\alpha}[x(t)] = L^{-1}\{s^{\alpha}X(s)\} \tag{3}$$

$$D^{\alpha}[x(t)] = \lim_{k\to 0}\left[\frac{1}{h^{\alpha}}\sum_{k=1}^{\infty}\frac{(-1)^{k}\Gamma(\alpha+1)}{\Gamma(k+1)\Gamma(\alpha-k+1)}x(t-kh)\right] \tag{4}$$

where Γ is the gamma function and h is the time increment. The implementation of the $PI^{\lambda}D^{\mu}$ is then given by:

$$G_c(s) = K\left(1+\frac{1}{T_i s^{\lambda}}+T_d s^{\mu}\right) \tag{5}$$

we adopt a 4th-order discrete-time Pade approximation (a_i, b_i, c_i, $d_i \in \Re$, k = 4):

$$G_P[z] \approx K\left(\frac{a_0 z^{k}+a_1 z^{k-1}+\cdots+a_k}{b_0 z^{k}+b_1 z^{k-1}+\cdots+b_k}\right) \tag{6}$$

where K_P is the gain.

If both λ and μ are 1, the result is a classical *PID* (henceforth called integer *PID* as opposed to a fractional *PID*). If $\lambda = 0$ ($T_i = 0$) we obtain a PD^{μ} controller. All these types of controllers are particular cases of the $PI^{\lambda}D^{\mu}$ controller.

It can be expected that $PI^{\lambda}D^{\mu}$ controller may enhance the systems control performance due to more tuning knobs introduced. Actually, in theory, $PI^{\lambda}D^{\mu}$ itself is an infinite dimensional linear filter due to the fractional order in differentiator or integrator.

In order to implement this control methodology in *Arduino*'s 8-bit microcontrollers, an easy to use *C* library of the fractional order *PID* controller was fully developed for *Arduino* boards and can be found in (Couceiro, 2011). The library consists on a collection of functions but can be easily used as it follows:

$$u(t) = fopid\left(e(t), \frac{de(t)}{dt}, \int e(t)\,dt, K, KT_d, \frac{K}{T_i}, \mu, \lambda\right) \tag{7}$$

As previously stated, the controller output $u(t)$ will be directly related to the input signal (*i.e.*, duty cycle of the *PWM* wave) of the pneumatic cylinder, thus controlling its position. The methodology used to tune the proportional, derivative and integral gains of the controller, respectively denoted as K, KT_d and $\frac{K}{T_i}$, and the fractional derivative and integral parameters μ, λ is presented in next section.

4.3 Controller evaluation

For controller tuning techniques, we decided to use the Particle Swarm Optimization (*PSO*) since it is a very attractive technique among many other algorithms based on population, with only some few parameters to adjust (Couceiro et al., 2009; Tang et al., 2005; Pires et al., 2006, Alrashidi & El-Hawary, 2006).

The *PSO* was developed by Kennedy and Eberhart (Kennedy & Eberhard, 1995). This optimization technique, based on a population research, is inspired by the social behavior of birds. An analogy is established between a particle and an element of a swarm. These particles fly through the search space by following the current optimum particles. At each iteration of the algorithm, a movement of a particle is characterized by two vectors representing the current position x and velocity v (Fig. 5).

The velocity of a particle is changed according to the cognitive knowledge b (the best solution found so far by the particle) and the social knowledge g (the best solution found by the swarm). The weight of the knowledge acquired in the refresh rate is different according to the random values ϕ_i, $i = \{1, 2\}$. These values are a random factor that follow a uniform probability function $\phi_i \sim U[0,\phi_{i\,max}]$.

```
Initialize Swarm
repeat
    forall particles do
        Calculate fitness f
    end
    forall particles do
        v_{t+1} = I v_t + φ1(b-x) + φ2(g-x)
        x_{t+1} = x_t + v_{t+1}
    end
until stopping criteria
```

Fig. 5. *PSO* Algorithm.

where I and t are the inertia and the time of iteration, respectively.

In order to evaluate the control architecture, we can use performance criteria (fitness f) such as the Integral Time Absolute Error (*ITAE*) proposed by Graham and Lathrop (1953).

$$ITAE = \int_0^{\infty} t.|e(t)|\,dt \tag{8}$$

Minimizing the *ITAE* is commonly referred as a good performance metric in the design of *PID* controllers since it can be easily applied for different processes modelled by different process models (Seborg et al., 2004). Using the *PSO* to minimize the *ITAE* offer advantages since the search of controller parameters can be obtained for particular types of loads and set points changes faster than using different metrics and different optimization methods such as the Gradient Descent (Couceiro et al., 2009).

Next section presents the experimental results of how the gains of the $PI^{\lambda}D^{\mu}$ were tuned as well as some trials performed by our putting mechanism.

5. Experimental results

In order to analyze the controllers' performances, a real-time data acquisition program was designed in *MatLab* to capture the system output data through the communication interface between the *PC* and the *Arduino* controller.

Experimental results were divided in two stages: *i*) Optimization and comparison of the integer and fractional order *PID* controllers; and *ii*) Evaluation of the proposed Putting Mechanism while simulating, under the same conditions, a set of 30 trials previously performed by an expert subject when facing a ramp constraint.

In all experimental results the system pressure was set to 6 bar and the controllers were updated each time the external interrupts were activated, thus computing the time between pulses.

5.1 Controller optimization

In this section we compare the performances of the classical and fractional order *PID* controllers (Ferreira et al., 2002) (Couceiro et al., 2010b).

Therefore, the duty cycle of the *PWM* wave is set as the controller output of the putting device. The *PSO* was set with a population of 100 particles with $\phi_i = 1$ and $I = 0.9$. The stopping criteria considered was a maximum iteration number of 200.

In order to study the device response to velocity inputs, two separated rectangular pulses of 400 mm.s^{-1} (*i.e.*, low velocity) and 1500 mm.s^{-1} (*i.e.*, high velocity) were applied, thus considering common values of putting impact velocities (Delay et al., 1997; Coello et al., 2000).

Under the last conditions, the following *PID* and $PI^{\lambda}D^{\mu}$ controller parameters depicted in Table 2 were obtained as being the ones that minimizes the *ITAE*.

Figures 6 and 7 presents a trial obtained using both *PID* and $PI^{\lambda}D^{\mu}$ controllers for each condition. It is noteworthy that controllers performance improves at higher velocities since the pneumatic cylinder used in the proposed putting device usually works at velocities near 1000 mm.s^{-1}.

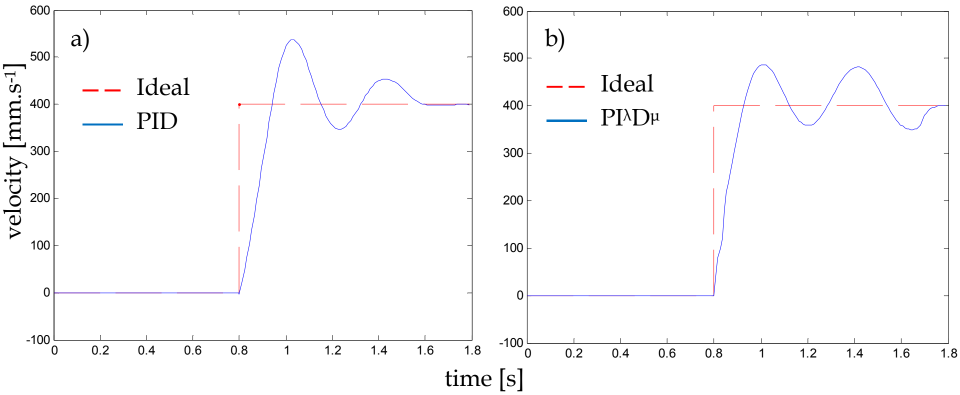


Fig. 6. Time response of the device with a putting impact velocity of 400 mm.s^{-1} under the action of the: a) *PID* controller; b) $PI^{\lambda}D^{\mu}$ controller.

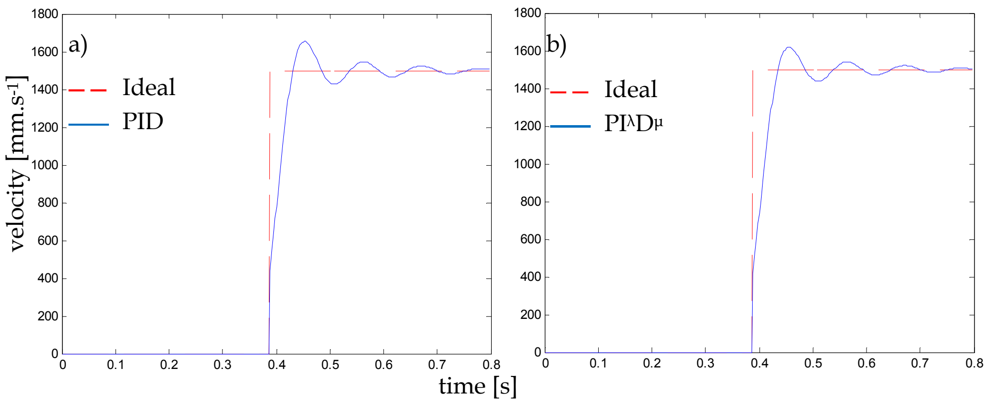


Fig. 7. Time response of the device with a putting impact velocity of 1500 mm.s^{-1} under the action of the: a) *PID* controller; b) *PI$^{\lambda}$D$^{\mu}$* controller.

	K	K/T_i	KT_d	μ	λ
PID	0,040	0,004	0,020	-	-
PI$^{\lambda}$D$^{\mu}$	0,004	0,040	0,015	0,76	0,64

Table 2. *PID* and *PI$^{\lambda}$D$^{\mu}$* controller parameters.

To analyze more clearly the dynamical response to the step perturbation, Table 3 compares the time response characteristics of the integer and the fractional *PID* controllers, namely the percent overshoot *PO*, the rise time t_r, the peak time t_p, the settling time t_s and the *ITAE*.

		PO [%]	t_r [s]	t_p [s]	t_s [s]	*ITAE*
400 mm.s^{-1}	*PID*	33,750	0,125	0,212	0,780	1,279x10^4
	PI$^{\lambda}$D$^{\mu}$	21,750	0,132	0,204	0,910	7,582x10^3
1500 mm.s^{-1}	*PID*	14,790	0,045	0,085	0,325	5,300x10^3
	PIλDμ	13,730	0,045	0,070	0,325	2,830x10^3

Table 3. Time response parameters of the device under the action of the *PID* and *PI$^{\lambda}$D$^{\mu}$* controllers.

Table 3 shows that, generally, the fractional order controller leads to a reduction of the overshoot, the peak time and the *ITAE*. However, it should be noted that the fractional order *PID* increases the computational cost of the microcontroller. While an iteration of the *PID* can easily run at each external interruption between two pulses at the maximum putting velocity of 3000 mm.s^{-1}, the developed *PI$^{\lambda}$D$^{\mu}$ Arduino* library sometimes loses pulses. The rise time t_r (*i.e.*, time required by the putting mechanism to reach the specified velocity) may be a consequence of this problem. Nevertheless, and since the putting mechanism benefit from a higher encoder resolution, the computational cost imposed by the *PI$^{\lambda}$D$^{\mu}$ Arduino* library does not jeopardize the performance of a given putting execution.

5.2 Evaluation of the putting mechanism

This section presents the accuracy of the putting device comparing it with real data obtained from 30 trials performed by an expert golf player with a handicap of 5.

In order to allow a straightforward comparison with the golf player, the mechanism was deployed in an artificial green to hit the ball two meters away from the hole (Fig. 8). The reference trajectory performed by the golf player at each trial was sent to the microcontroller through serial communication[1].

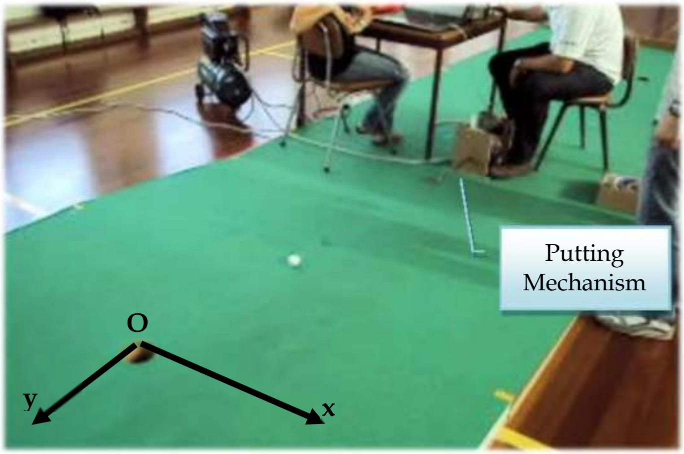


Fig. 8. Experimental setup to evaluate the putting mechanism in an artificial green with ramp.

The analysis of a set of trials is not directly accessible and need a graphical or geometrical representation. To analyze the radial error, which may be calculated using the lateral error (x-axis) and longitudinal error (y-axis) within the sport context, one of the most common representations is the error ellipse. The error ellipse allows a two-dimensional graphical analysis representing the influence of the lateral and longitudinal error (*i.e.*, accuracy) and the variability (*i.e.*, precision) of a given player (Mendes et al., 2011). By observing the shape, size and orientation of the ellipse, one can easily compare different players or, as it is presented in this book chapter, compare a man with a machine. Figure 9 depicts the error ellipse of both the golf player and the putting mechanism.

As it can be observed, there is a high similarity in the shape of both ellipses. It is noteworthy that the golf player was more accurate than the developed mechanism since it only missed 4 trials (accuracy of 86,67%) against 11 missed trials from the device (accuracy of 63,33%). However, the area of the ellipse for both the player and the putting mechanism was 2,2052 m^2 and 1,7536 m^2, respectively. This means that, despite the higher accuracy of the human player, the device was more precise thus presenting a lower variability.

[1] A video of the experiments is available at http://www2.isec.pt/~robocorp/research/putting/

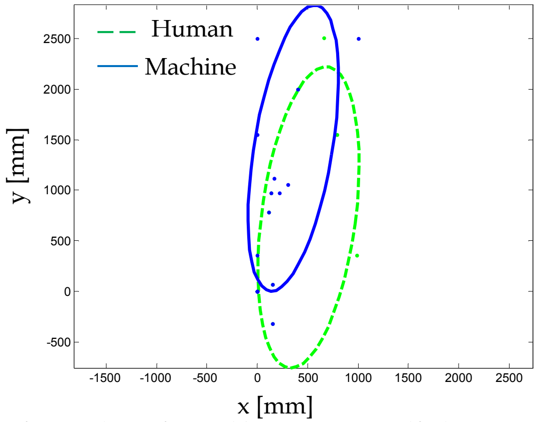


Fig. 9. Error Ellipse of 30 trials performed by an expert golf player and subsequently emulated by the putting mechanism.

6. Conclusion

This book chapter presented an experimental device to evaluate the golf putting. The proposed mechanism is similar to other mechanisms and robotic devices presented in the literature (*cf.* Related Work section), and it is the authors' opinion, that the great advantages of other mechanisms are their mobility and sensory system (*e.g.*, vision). However, since the scope of this work consists on executing the putting as an isolated movement to unveil the process and product variables, the proposed solution can be characterized by having a small size (*i.e.*, easy to transport and apply in any situation) and high reliability (*i.e.*, capable of emulating real kinematical data obtained by expert golf players). Despite these advantages, like other experimental devices, although this mechanism can simulate the putting, it can hardly represent unequivocally the motor performance of a human being, because, as expected, each individual has different characteristics and profiles that represents a "putting signature" distinct from subject to subject, which, may not be fully replicated by a robot.

Hence, man versus machine analogy is inevitable and strides for the multi and interdisciplinary research that crosses knowledge of several research fields (*e.g.*, engineering, sport science and biomechanics) to meet the challenges in science. Thus, this work, more than just presenting a mechanism or experimental device that can replicate the putting gesture, it is worth for proposing a novel creative process that can serve as support for future researchers who wish to further study this movement.

We emphasize that already in 1940, Nicolai Bernstein, a Russian physiologist that studied the "mechanics" of the human upper limb, said that it is virtually impossible to replicate two motions exactly the same way. Since then, this researcher paved the way to study the human movement in a global perspective closer to the variability that characterizes the human movement systems (Bernstein, 1967). In addition, the "body machine" designed by Descartes can become a reality in the future, winning the "body of emotion" of Benedict Spinoza (1989, 1992), which, in a society increasingly dependent on robots, may become an inevitable Matrix, where the study of the body phenomenology reported by philosophers such as Plato, Aristotle and Socrates is worth another look (Merleau-Ponty, 1964). As referred by Gaya (2005), the study of the "contemporary body" in the age of technoscience aims the hybrid body to overcome all imperfection of the biological body.

In summary, this study, which analyzes the golf putting, *i.e.*, a gesture made by the human body in sports context, may be further studied in conjunction with other scientific areas, thus benefiting from their contributions, either in laboratory context or in real teaching and learning situations.

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First placed on the market in 1939, the design of PID controllers remains a challenging area that requires new approaches to solving PID tuning problems while capturing the effects of noise and process variations. The augmented complexity of modern applications concerning areas like automotive applications, microsystems technology, pneumatic mechanisms, dc motors, industry processes, require controllers that incorporate into their design important characteristics of the systems. These characteristics include but are not limited to: model uncertainties, system's nonlinearities, time delays, disturbance rejection requirements and performance criteria. The scope of this book is to propose different PID controllers designs for numerous modern technology applications in order to cover the needs of an audience including researchers, scholars and professionals who are interested in advances in PID controllers and related topics.

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