Design and Implementation Solenoid Based Kicking Mechanism for Soccer Robot Applied in Robocup-MSL

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Abstract: *RoboCup is an international competition to prompted robotics and related subject like: Artificial intelligence, Image processing, control, devise design and etc. One of the subjects in RoboCup competitions is Soccer. Naturally robotic soccer is an interactive and complex procedure. it might be so idealistic, but some consider a challenge with a real human football team in 2050 , as the final goal of robotic soccer. There are several classes in robotic football matches such as: Middle size, Small size, simulation and so on. One of the most essential parts of a soccer robot in Middle size and Small size classes in the kicking system, this system is in charge of kicking the ball upon the command issued by the processor of robot. Almost every team develops their own unique shooting device. There are three main approaches to design and implement the robot kicking system. In this paper we designed and developed multi power kicking system that enables loop and vary shooting power. To design a good solenoid and to obtain maximum velocity of ball some parameters like: inductance, response time, resistance, force, dimensions and core-material should be balanced carefully. We used a DC-DC converter (Boost regulator) for getting different currents to have different power of shooting. We are going to review the advantages of all of those approaches. Next we are purposes a novel Solenoid-based kicking system which has already been successfully implemented in Adro RoboCup team.*
Keywords: *Magnetic Gun, Kicking Mechanism, Magnetic Field, Solenoid, RoboCup.*

1. Introduction

Robocup is an international project to promote robotics and subjects related like AI (Artificial Intelligence). It is founded to make a contribution to Artificial Intelligence and intelligent robotics research. Robocup chose to use a soccer game competition, because of the great complexity of this game. The final goal is to be able to win against the human world champion team in soccer in the year 2050. One of the main part of robots which play in Middle size and Small size leagues of Robocup matches is Kicker system [1, 2]. This system most kicks the ball when a specific control command come from processor of robot. Almost every team has developed their own unique shooting device. They can be subdivided into three categories which will be dealt in this paper.
In this paper the choice and development of the best shooting mechanism for Robocup Middle size and Small size league will be taken into account. The first section contains an overview of already used mechanisms by other teams. The second section contains comparison, demands and the best mechanism will be chosen. This mechanism will be explained in the final section followed by a design.

2. Kicking Mechanisms used in Robocup

In this section, all of the shooting mechanisms used in Robocup competitions will be discussed. Although every team is developing its shooting system all the time, as a whole we can divide all the mechanisms of Robocup in to three groups:

a) Stroke mechanism through spring.
b) Stroke mechanism through pneumatic.
c) Stroke mechanism through solenoid.

These three mechanisms will be compared with each other in eight cases, then the best shooting mechanism for middle size soccer Robots will be chosen and developed.

- Shooting power
- Weight
- Space required
- Time between shots
- Safety
- Simplicity
- Number of shots
- Cost

2.1 The Stroke Mechanism Through Spring

The first kind of stroke mechanism is the one based on storing energy in a spring through a DC engine. One of the outstanding properties of this mechanism is its simplicity. The spring, in this system, is contracted and maintained through a DC engine and is released at determined time. One standard kind of this mechanism is illustrated in the following figure.

If this system is well designed, it can enter a strong stroke to the ball, because we can store a lot of energy in the spring. The numbers at strokes in this mechanism are unlimited and it just depends on the battery. This system has some defects such as: the large space it requires, its high weight, the amount of time it takes to recharge and the main defect of the shooting mechanism through spring is that controlling the force for shooting is difficult.

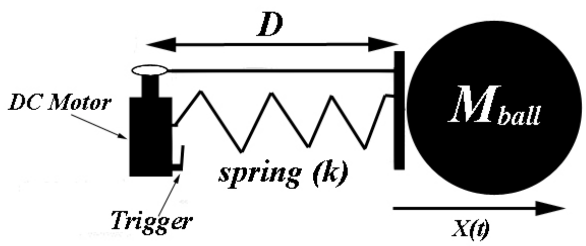

Fig. 1. Schematic of Spring-base shooting mechanism

Shooting Power	+
Weight	-
Space required	-
Time between shot	-
Number of shots	+
Safety	+
Simplicity	-
Cost	+

Table 1. Overview of spring base shooting mechanism

2.2 The Stroke System Through Pneumatic

The second mechanism which is to be discussed is the one based on pressure and pneumatic. Pneumatic is a very simple technology for stroking mechanisms in the RoboCup competitions.

In this mechanism, a huge tank will be designed and installed somewhere in the Robot, then pneumatic jacks which are connected to the gas resource, will be established in front of the Robot or on some sides of it. The gas resource will be filled before every competition. Because in the pneumatic jacks switch actions are done through solenoid, we can somehow control the stroke. In general, the following cases are some defects of the above system: The strength of the stroke depends on the amount of gas in the tank, it requires a huge space, and the numbers of strokes are limited in a competition.

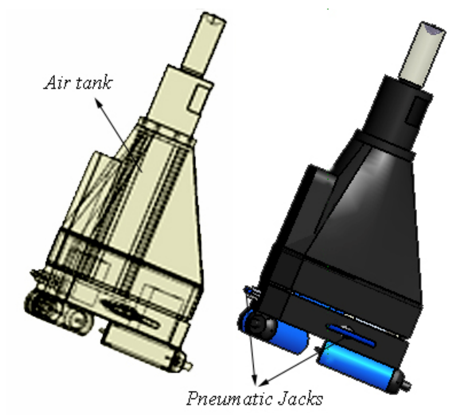

Fig. 2. Schematic of Spring-base shooting mechanism

Shooting Power	-
Weight	-
Space required	-
Time between shots	+
Number of shots	-
Safety	+
Simplicity	+
Cost	+

Table 2. Overview of pneumatic base shooting mechanism

2.3 The Stroke System Through Solenoid

The third idea for shooting mechanisms is through an inductive resistance in which when the electricity passes through a solenoid, a magnetic field will be created. When we increase the number of cycles or the amount of electricity, there will be a stronger magnetic field. The Magnet materials can be absorbed or repelled through a magnetic field and this is a phenomenon which is used in building solenoid.

Since the available solenoids are flat and wide and have low voltage, they have a fairly slow movement, so they are not suitable for shooting mechanisms. The solenoids for shooting should be fast and should require a small space. For example, they should be totally about 20cm and with the speed of 10 m/s. For this reason, each team will design a specific solenoid for itself. The figure below shows a general and simple mechanism of a solenoid.

In designing a solenoid, we should use all the properties of a Magnet nucleus so that a suitable magnetic field will be created at the center of the solenoid nucleus to absorb the iron piece (the shaft iron piece is made up of the materials which have high magnetic properties).

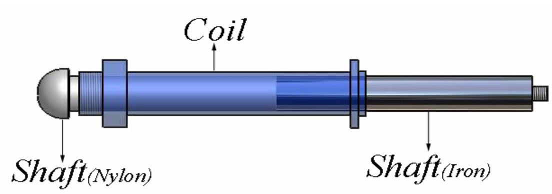

Fig. 3. Solenoid mechanism system

Shooting Power	+
Weight	+
Space required	+
Time between shots	+
Number of shots	+
Safety	-
Simplicity	+
Cost	+

Table 3. Overview solenoid base shooting mechanism

Using the solenoid based mechanism, the Robots can shoot rapidly. For example, in order to enter a stroke by which the speed of the ball increases to more than 10 m/s. The Robots need a nucleus with 800 turns and a current of 60 [A]. In the electronic board we need a DC to DC converter, a condenser with high capacity, a few resistances and a switch element part. This theory for creating a solenoid is both suitable and reliable. Another important point is that the amount of time the electricity is in circulation in the solenoid nucleus can control the shooting power. One of the defects of this system is the source with very high voltage and electricity (a condenser with high capacity). In order to solve this problem, we should put the source in a firm, non conductor, and out of hand box.

3. Comparison

Different cases of shooting mechanism with the advantages and disadvantages of each case, was discussed in the previous section. Now we can design the considered mechanism through determining the need and requirements and doing a comparison.

3.1 Determining the Needs and Requirements

According to the RoboCup regulations, each robot should be designed with a specific size and each robot with its attachments should not be more than a 50*50 square but it can be more than this size, for example 60*60, at the time of shooting or dribbling.

Therefore in normal situation, the shooting mechanism should not more than 10 cm.

The shooting mechanism of a Robot should be designed so that it can enter controlled and precise strokes in different conditions. For example, the start of the play, or passing and shooting from different points of the ground to the gate need controlled and precise strokes. An appropriate shooting system should also be able to enter a stroke to the ball with the speed of about 10 m/s, because the gate-keeper and other Robots are not so rapid and agile that can analyze shooting before the ball enters the gate and move towards the considered point.

The amount of energy required for shooting with the speed of 10 m/s is calculated with the below formulas. To calculate the speed of the ball we suppose that after entering a stroke to the ball, the ball is completely rotating and the stroke between the ball and the shooting mechanism should be completely elastic and we ignore friction and air resistance:

$$\frac{1}{2} m_{planger} v_{Planger}{}^{2} = \frac{1}{2} m_{ball} v_{ball}{}^{2} + \frac{1}{2} J_{ball} w^{2} \quad (1)$$

$$J_{ball} = \frac{2}{3} m_{ball}\ r_{ball} \ = 363 \times 10^{-3} \left[Kg \cdot m^{2}\right] \quad (2)$$

$$w = \frac{v_{ball}}{r} \left[rad/s\right] \quad (3)$$

With these relations the amount of energy will be 42,5[J].

In order to have the most security and reliability, we should consider some points For example, in some cases some Robots may want to shoot more than once, the amount of time for reload time should be as short as possible and with respect to shielding we should avoid noise spreading can impact greatly on different parts of a Robot. To put it another way, the shooting system should not have any effect on controlling other parts and it should be designed so that the

Robot can remain rapid and agile, on the other hand, the space required for the shaft and the solenoid coil should be as small as possible because he shooting mechanism at the lower part of the robot is next to the other factors such as engines and ball handling.

3.2 Choosing the Best Mechanism

We investigated different shooting mechanisms available for Robocup at the beginning of the article, and then we determined all the needs and requirements from a shooting system. Now we put all the information obtained from previous sections in a table to compare the three mechanisms with each other and choose the best one.

After comparing the shooting mechanisms through table4, we conclude that the stroke mechanism through solenoid is the best choice. We will consider the solenoid theoretically and practically in the following parts.

Properties	Spring	Pneumatic	Solenoid
Shooting Power	+	-	+
Weight	-	-	+
Space required	-	-	+
Time between shots	-	+	+
Number of shots	+	-	+
Safety	+	+	-
Simplicity	-	+	+
Cost	+	+	+

Table 4. Over view of all shooting mechanism

4. Designing the solenoid

In designing the solenoid, we should consider different factors which determine the behavior of the solenoid in different conditions. These factors are:

- Inductive resistance
- Resistance

- Force
- Size
- The source for voltage nourishment
- Feedback time

For designing an appropriate solenoid, we should select all the effective parameters accurately and precisely. We will consider the details of the above parameters in the following section [3, 7].

4.1 Inductive Resistance (Self-Inductance)

We can calculate the inductive resistance of a solenoid through the number of circles of the solenoid of the length and thickness by the following formula (note that this formula is for when the solenoid shaft is not in it, this amount is not constant, and this resistance will increase when the solenoid shaft is moving in it):

$$L[mH] = \frac{0.0315 \times N^2 \times \left(\frac{R_1 + R_2}{2}\right)^2}{6 \times \frac{R_1 + R_2}{2} + 9 \times l_{Coil} + 10 \times (R_2 - R_1)} \quad (4)$$

Where N is the number of turn, R_1, R_2 are defined as the inside and outside radius[m], l_{Coil} is the Length of the solenoid coil [m] and L is self inductance [mH].

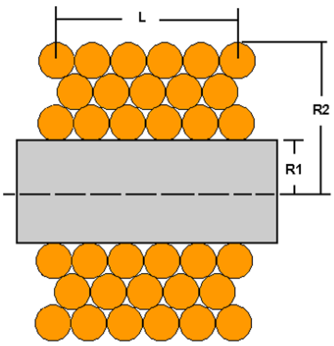

Fig. 4. Crossection of a soelnoid

4.2 Resistance

We can calculate the resistance of a solenoid with respect to the resistance of the solenoid. For calculating the resistance of the solenoid, we need the thickness of the wire, the kind of the wire, and its length. The length of the wire can be calculated through the following formula:

$$l_{wire} = 2\pi \times \left(R_1 + \frac{(R_2 - R_1)}{2}\right) \times N \quad (5)$$

Solenoid is often made up of a coil from copper because copper is good conductor and is easily available. The resistance of coils is often measured through the following formula:

$$R = \rho \times l_{wire} \quad (6)$$

Where R is the resistance [Ω], ρ is the resistance by unit length [$\Omega \ m^{-1}$] and l_{wire} is the wire length [m].

4.3 The solenoid Force

For calculating the solenoid force, we can use Lorentz formula:

$$F = B \times l \times I \quad (7)$$

Where B is the flux density [T], I is the current by unit Ampere [A] and l is the solenoid coil length [m].
According to the above formula, the solenoid force is equal to the current and the length of the solenoid nucleus so that for high current, the force is appropriate for the current, because a strong shooting needs the energy to increase just in the realm of high current [3,7].

4.4 Dimensions

For a concentrated magnetic field, the solenoid should be designed so that:

a) The shaft is near the solenoid coil.

b) The length of that part of the shaft which is magnetic is equal to the length of the solenoid coil [4].

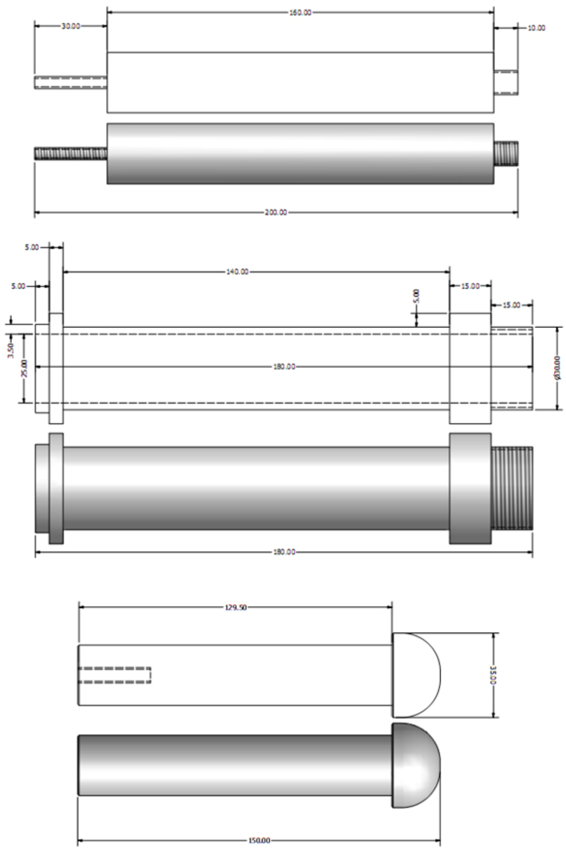

Fig. 5. Prototype drawing of a soelnoid

4.5 Shielding

For improving the solenoid, we need to control the magnetic field radiated form the coil as high as possible and avoid its effect on other parts of the robot. Shielding is possible through a steel tube out of the solenoid and in its tow ends. Increasing the shielding will decrease the magnetic resistance (reluctance) out of the solenoid (The reluctance is similar to the electricity resistance).

4.6 Time Constant

When a current is present in the coil, a magnetic flux through the coil is built up. This flux changes when the current changes. So, a coil that carries a varying current has an electomotive force (EMF) induced on it by the variation in its own magnetic field. This self inductance is simply called inductance. The self-induced EMF ε in a coil is given as:

$$\varepsilon = -L\frac{dI}{dt} \tag{8}$$

The SI unit for inductance is Henry (1 H = 1 Ω s). Lenz's law says that the self-induced EMF in a circuit opposes any charge in the current in that circuit.

This all means that it is difficult to rapidly change a current through a circuit which includes an inductor. The inductor in this case is the coil of the solenoid. The coil is normally modeled as a R-L circuit (a circuit that includes a resistor (R) and an inductor (L)). The growth, in time, of the current is first order

$$I = \frac{\varepsilon}{R}\left(1 - e^{-\left(R/L\right)t}\right) \tag{9}$$

At a time equal to L/R, the current has risen to (1−1/e). The quantity L/R is a measure of how quickly the current builds up towards its final value. This is called the time constant. The time constant for an R-L circuit, denoted by τ, is

$$\tau = \frac{L}{R} \tag{10}$$

In a time equal to τ, the current reaches 63% of its final value; in 2τ, 86% and in 5τ , 99.3%. The growth (and decay) of the current is show in Figure5 [3].

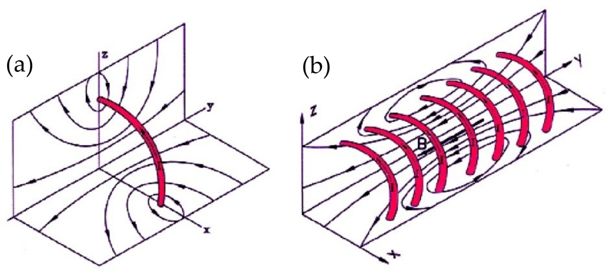

Fig. 6. (a) The magnetic field of a circular current loop and (b) the magnetic field of a solenoid.

For the working principle of the solenoid, this means that the plunger most be held on its initial position. When the current is at a certain level, the plunger must be released. Then the solenoid works at maximum efficiency and power [5].

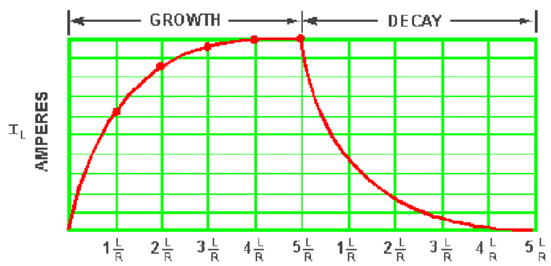

Fig. 7. Time constant of the solenoid coil

5. Final Design

As it was mentioned before, all of the effective parameters in designing an appropriate solenoid for a RoboCup should be selected accurately and precisely.

The most important parameters are accurate calculation of the thickness of the coil wire, the length of solenoid and the availability of the component for designing the solenoid circuit.

A solenoid with a proper stroke for shooting system requires a high current which passes an coil with low inductive resistance; therefore, according

to the rule of Ohm, the result will be a high voltage For storing the energy, we used a capacitor with high capacity about 450 volt, the capacitor is charged through a switching circuit to 450 volt , thus the maximum voltage which can be imposed to the solenoid will be 450 volt .

For solenoid able to enter a stroke with the speed of more than 10m/s, we need a force about 45j. This force will be created with a coil with 923 circles in 6 layers with a wire which has 0.65mm thickness and 450V voltage. The inductive resistance can be calculated through the following formula. The length of the solenoid should be about 10 cm because of its high ferromagnetic ability and Polyetalon is selected for it has appropriate density and mass for movement and interaction with the ball.

The gap space between the shaft and solenoid nucleus is about 1mm. the distance between the coil and gap is bout 1.5mm. the body of solenoid nucleus is form polyamid because it is very firm and has proper weight. The shield around the solenoid is form steel and has 2mm thickness [6].

5.1 Designing the solenoid circuit

In this section we will discuss a circuit which can produce enough voltage for solenoid and witch can control it. We will consider the solenoid circuit in two parts:

- DC-DC converter circuit
- The solenoid controlling circuit

5.1.1 DC-DC Converter Circuit

In this part, we will introduce a generate circuit able to produce the appropriate voltage for the solenoid. DC-DC converters are electronic devices used whenever we want to change DC electrical power efficiently from one voltage level to another. They're needed because unlike AC, DC can't simply be stepped up or down using a transformer. In many ways, a DC-DC converter is the DC equivalent of a transformer. There are many different types of DC-DC converter, each of which tends to be more suitable for some types of application than for others. For convenience they can be classified into various groups, however For example some converters are only suitable for stepping down the voltage, While others are only suitable for stepping it up; Another important distinction is between converters which offer full dielectric isolation between their input and output circuits.

- ✓ **Non-Isolating Converters**: The non-isolating type of converter is generally used where the voltage needs to be stepped up or down by a relatively small ratio. There are five main types of converter in this non-isolating group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down/reduction, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step-down or step-up, but are essentially voltage polarity reversers or .inverters. As well. The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications. We're going to look briefly at Boost DC-DC converter for producer a suitable voltage for solenoid.
- ✓ **Boost Converter:** The basic boost converter is no more complicated, in order to step up the voltage. Again the operation consists of using Q1 as a high speed switch, with output voltage control by varying the switching duty cycle. When Q1 is switched on, current flows from the input source through L and Q1, and energy is stored in the inductor's magnetic field. There is no current through D1, and the load current is supplied by the charge in C1. Then when Q1 is turned off, L opposes any drop in current by immediately reversing its EMF. So that the inductor voltage adds to the source voltage, and current due to this boosted voltage now flows from the source through L, D1 and the load, recharging C1 as well. The output voltage is therefore higher than the input voltage, and it turns out that the voltage step-up ratio is equal to:

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{(1-D)} \tag{11}$$

Where 1-D is actually the proportion of the switching cycle that Q1 is off, rather than on. So the step-up ratio is also equal to:

$$\frac{V_{OUT}}{V_{IN}} = \frac{T}{T_{OFF}} \tag{12}$$

If you work it out, you find that a 2 :1 step-up ratio is achieved with a duty cycle of 50% ($T_{ON} = T_{OFF}$), while a 3:1 step-up needs a duty cycle of 66%Again, if we assume that the converter is 100% efficient the ratio of output current to input current is just the reciprocal of the voltage ratio:

$$\frac{I_{IN}}{I_{OUT}} = \frac{V_{OUT}}{V_{IN}} \tag{13}$$

So if we step up the voltage by a factor of 2, the input current will be twice the output current. Of course in a real converter with losses, it will be higher again.

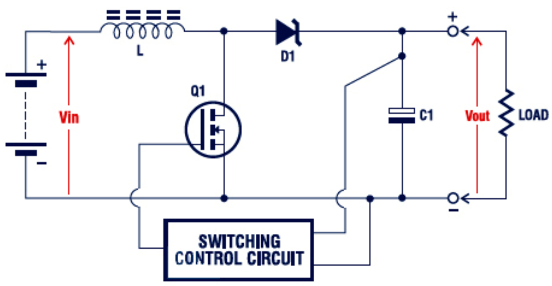

Fig. 8. The basic circuit for a Boost converter

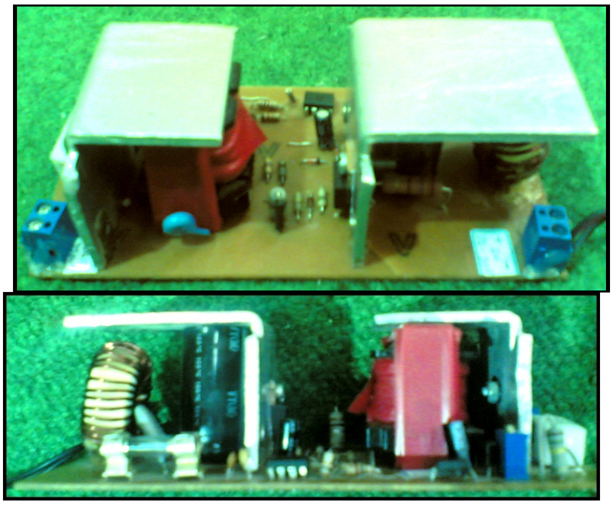

Fig. 9. Power modulation: 12 volt to 450 volt converter

5.1.2 The solenoid controlling circuit

Through this circuit, the time needed for first charging of the condenser to 450V, is 13 seconds. This voltage will be about 150v after a stroke with the maximum force. The time need for recharging the capacitor from 100 volt to 450 volt is about 9 seconds. Parallel to the capacitor is the solenoid, modeled with a coil and a resistance with the values of the Robocup solenoid. The solenoid is connected to a transistor which is controlled by a pulse source. The transistor can handle high currents (IRG4PC50FD) .When the source-signal is high the transistor is closed (solenoid is activated), when low it is open (solenoid is idle). The transistor opens in 380 [ns] and closes in 70 [ns]. Specification sheet is available in attachment 2. Parallel to the solenoid is a diode with a resistance to"catch" the back-current generated when turning of the solenoid.

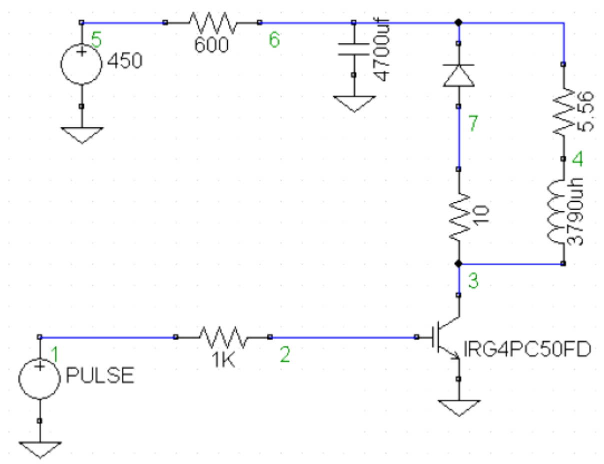

Fig. 10. Solenoid controlling circuit

The solenoid designing for the normal conditions is not able to return to the first place after the stroke, because after imposing and cutting the voltage from Solenoid, its shaft will be stopped in the last possible place. For returning it to its first condition, we should use another mechanism. This returns the solenoid to its first place after the stroke. An easy and cheap solution for the above problem is using a spring at the end of the solenoid.

6. Conclusion

The solenoid is the best option for a RoboCup shooting device. It is powerful, not very expensive, robust, lightweight and small. It is also able to modulate shooting power by applying pulse width modulation on the pulse source in the control circuit.
The shooting device is also ready use in much Robocup competition. The performance of our robot team in Iran-Open RoboCup competitions 2008 (1st place) showed that the combination of methods and techniques described in this paper are led to a successful design and implementation of a solenoid based kicking mechanism for soccer player team. In our robot, omnidirectional navigation system, omni-vision system and a powerful kicking mechanism have been combined to create a comprehensive omni directional robot. It's expected (and one of our goals) that in the near future robots can pass to other robots.

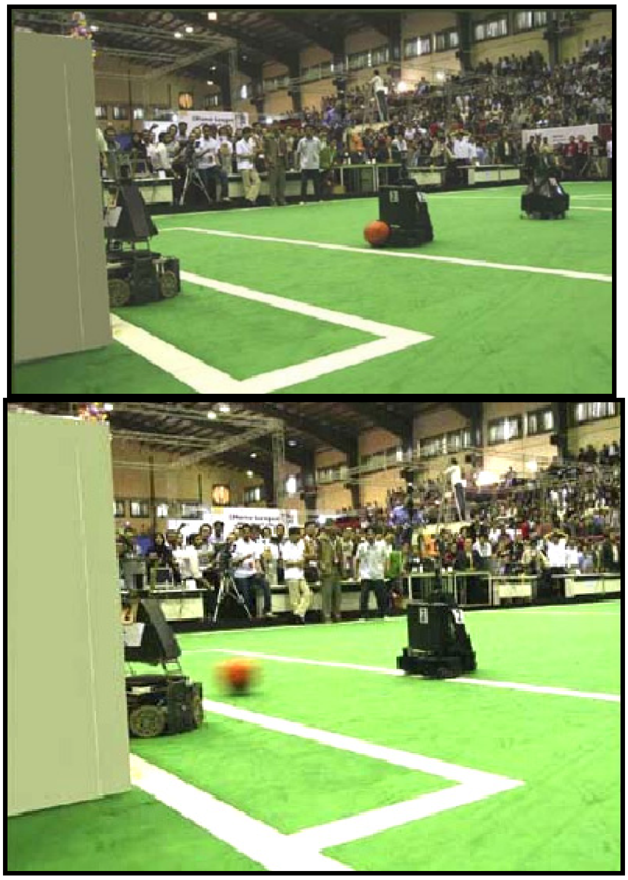

Fig. 11. ADRO RoboCup Team in Iran-Open RoboCup Competition

Further information's and video about our works are presented on our website: http://www.IranAdro.com

7. Acknowledgment

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