VIOLIN-BOT PLAYER

ABDELATI ZELBANE

azelbane@gmail.com
gameadebuck@yahoo.it

M00374639

Table of Contents

1. ABSTRACT

Violin-Bot_Player is a programmable device/machine that plays the violin. The main mechanisms are related to the bowing and the fingering processes. Different approaches have been considered for the bowing system in order to achieve a nice and smooth sound and a final decision have been made; also for the fingering system, a device made out of an arrangement of push type solenoids have been developed in order to imitate the violinist fingers. In this case for the complexity of the system itself and the very nature of the violin, the distances between one solenoid and the other have been made fixed; in order to play a particular note which is placed between two notes, the whole configuration of the solenoid could slide along the violin fingerboard: this kind of approach allows playing at list the first full octave on each string. In this document first is given an introduction of the musical instrument and a basic description of the physics behind the sound that it can produce.

2. INTRODUCTION

Since younger age I was fascinated by this incredible instrument for its physical appearance and for the sound it can produce able to penetrate the deepest emotion of the man. I personally had the chance in the past to play violin for 4 years and since then it became something that I had to discover and better understand by myself and very soon it also became one of my favourite hobbies. Having the chance to apply concepts of mechatronics engineering, in terms of designing, building and programming a device or machine, I chose to dedicate a more detailed research about the violin.

The inspiration of developing such a device is also addressed to Mills Violano Virtuoso machine, that I define as engineering marvel: it will be described afterwards in it this content.

First of all there is the need to understand what kind of physical properties are involved in order to replicate their functionality and come up with a programmable device that would eventually play the violin.

Also from personal direct experience, as D. Young(2001) stated, the act of bowing synchronized with fingering it is not just a matter of mechanical action of the fingers and arm, but it is also the passion and the emotional state of the player that produce the magnificent melodies; therefore the idea of designing a device is limited to its mechanical functionality and its reliability.

After detailed research the violin revealed its complexity challenging engineers and students to build a programmable device capable of autonomously perform it.

As will be described in the following context, many people in the past have been trying to come up with different ideas, approaches and techniques, some of them revealed to be successful and still are used today, for example the mechanisms used for the bowing action: many have tried a robotic arm exactly as a human; many others had simpler approaches consisting of a sliding mechanism of the bow adopting different ideas and concepts, like a loop of horsehair around 2 wheels to emulate the bow, or single horsehair wheels each one placed on a string, or the actual bow stroking over the strings by a sliding mechanism.

In the following content there are all the steps that have been taken in order to make the final decision which leads to the final construction of an acrylic device controlled by Arduino to synchronize the bowing system with the fingering mechanism.

It is important to mention that several mdf prototypes having the same design have been made and tested improving each time a particular component of the structure; the final prototype still has exactly the same design and it has been printed in transparent 3mm acrylic.

2. HISTORY

The violin is the smallest string instrument in its family after the viola, cello and double bass, and it is also the highest in pitch.

The violin can be thought as an instrument that evolved with the time rather than been thought as an invention made at once in a determined moment on time.

In fact it is believed that strings musical instruments have be introduced into the European culture by ancient Arabic and Asian merchants; initially the violin had a very different shape from the one we know today with a larger pear-shape body with a long neck and 3 strings with simple round sound-holes; as the instrument developed also the size and the shape changed with a gradually and great improvements: the strings became 4 tuned in fifth, the sound-holes took the f shape that we know today and also a more accurate design of the most critical components such the bridge, which is the part that holds the strings between one extreme of the violin to an other, have been made.

PICTURE 1   2 different types of violins belonging to Renaissance Period

During the 16th till the 18th century in north Italy, the violin reached its maximum pick in terms of development from both design and performance points of view. During this period a deep knowledge and scientific methodology on its construction have been made and it is not surprising that today we have the tendency of appreciating the shape and the sound that this instrument can produce, because “luthiers” adopted a rigorous harmonic balance over the sizes by applying the known concept of golden ratio, which at that time was considered as standard mathematical tool to obtain natural harmonic balance, either in music, architecture, sculpture, painting and many other varieties of art.

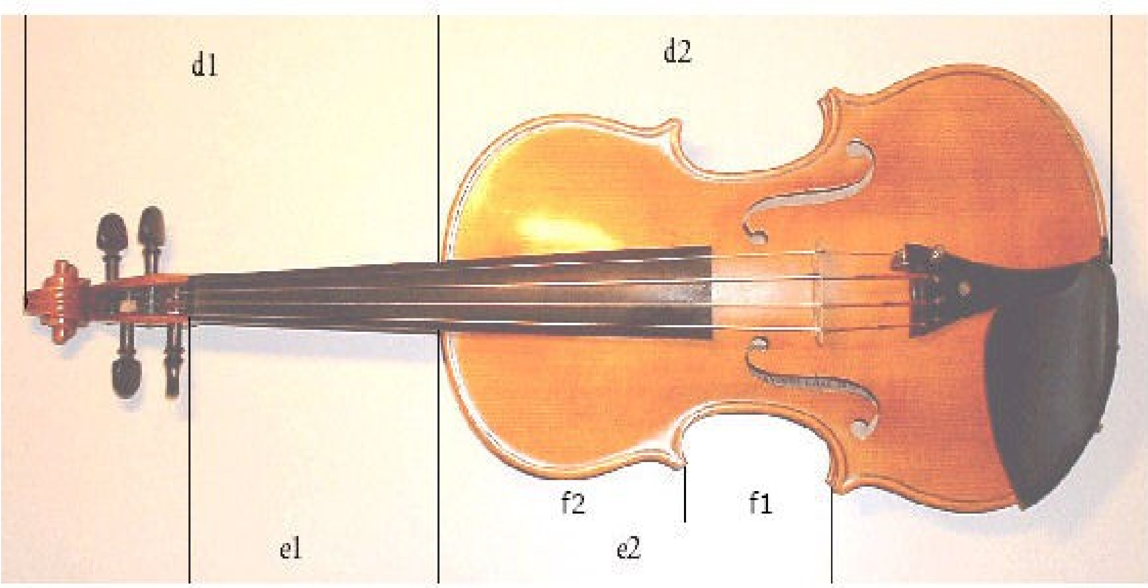
During the Renaissance, many have tried to standardise a reasonable size as well as a great and clean sound production of this instrument, until when the idea of applying the concept of harmony was introduce by the well known golden ratio.

To better understand the concept of the golden ratio which is present in many other examples in nature such as the human body size, here is an example: consider a length divided into 2 generic segments a and b: the golden ratio(indicated with the Greek letter "phi") is defined as the ratio between the short segment and the long segment, as well as the ratio between the long segment and the overall length.

PICTURE 2 Algebrical demonstration of the golden ratio (Google, 2014)

This relatively simple principle, which can be mathematically determined (phi=1.618033988...) is applied in order to size all the parts of the violin as the picture 3 shows.

$$\frac{d1+d2}{d2}=\frac{d2}{d1}=\frac{e2}{e1}=\frac{e2}{f2}=\frac{f2}{f1}$$



PICTURE 3 Violin sizes related to the golden ratio. (Johann Goldfuss, n.d.)

2.1 STRINGS

There are 4 strings in the violin, the lowest one is the G followed by D, A, E. Initially they were made of intestines of sheep, called "cat-gut", being stretched, sun dried and then twisted in a particular spiral way. This kind of strings have been used extensively during the baroque period and today is still used in very rare and extremely accurate performances.

However cutgut strings, since it is biological material, have the tendency of deteriorate and therefore needed to be replaced often and often. Today they have been replaced by nylon strings which revealed to be a cheaper and more reliable material. Thanks to its physical properties, the nylon can produce the same worm sound as cutgut string would do Patrizio Barbieri(February 1991), but definitely lasts much more and keeps the same brightness of the sound constant over the time.

However the most common violin string type is the metal string, also called steel core string: according to Erik Jansson, this could be a single core as well as a multi core string; this core then is covered by several windings of very fine metal in order to increase the mass (weight) of the string but without affectively changing the stiffness of the core, therefore no much affect will occur on the brightness of the sound.

2.2 TECHNIQUE

The violin is played by stroking the bow over 1 or 2 strings simultaneously; the right hand is holding and moving up and down the bow; the left hand is pressing the strings down against the fingerboard with the fingers. Usually the violin is held on the left shoulder and put in place by the jaw, which is connected to the violin via clamping mechanism and pressing the body of the violin against the shoulder.

When playing the violin, the position of the bow causes the change of the timbre significantly. If the string is excited on the fingerboard, the sound is clearly more mellow and it becomes hard and metallic if the bow is closer to the bridge; tilting the bow obviously diminishes the surface contact, which is the surface determined by the horsehair along the bow, hence affecting the sound by changing the amplitude: this is called tilting angle of the bow (Kristoffer Jensen, 1996).

The bow is made of many layers of horse hair which touches the strings when the bow slides down over them obtaining a more "hard" and louder sound than when the bow tilts at an angle. The sound also becomes brighter when the bow tilts rather than when it completely touches the string; the

same effect is obtained also when the force (pressure) of the bow is kept low.
Considering the bow sliding all the way about its length, the angle between the bow and the string can also be changed even though it is not a common practice among violinists: if this angle is not 90 degrees, the sound clearly becomes harsh, in-harmonic: this is due the longitudinal vibrations of the string (Frederic et al., 2011)
With the left hand it is possible to control the pitch of the note and it is achieved by moving up and down the fingers along the fingerboard, thereby changing the length of the actual string.
The very position of the finger on the string played causes the change in timbre as well as the pitch, also the pressure of the finger against the string can slightly change the timbre.

2.3 ARCHITECTURE AND MECHANISM

Today the violin is made with special and carefully designed tools that would shape a wooden almost hollow box with attached to it a neck; the side cuts of the violin are called ribs. Exactly underneath the lowest string is placed a vertical hard-wooden piece (*soul*) that runs between the belly and the back and has a double function: reinforcing the belly itself and also transmitting the actual sound inside the box.
The 4 strings run from peg-box, where are wounded around corresponding tuning pegs, till the end back of the violin through the bridge: this particular piece has been defined as one of the most important components of the instrument: in fact it holds the strings giving them steadily controllable tension through the pegs (and doing so gives to the strings the "arched configuration"), and also transmits vibrations straight underneath to the *soul*. (F. Ablitzera and J.P.Dalmont, 2010,2011)
The violin performance is something that clearly catches the attention of the audience and is enhanced by the very bowing gesture: each violinist has a different style and attitude towards the play he is going to perform. Some of them seem to play delicately the notes by sliding the bow following the smooth motion of the arm, some other violinists play the notes with much more force and they seem to attack the strings in order to achieve that particular kind of pitch, some others jump from string to string with energy, and each of these approaches dictate the final sound and the overall performance. Hence the very bowing gesture heavily determine the sound produced, and all these gestures are driven by the physical constrains defined by the following parameters as E. Schoonderwaldt reported in his work.

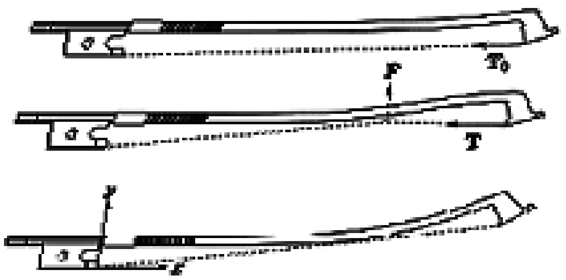
2.4 THE PHYSICS BEHIND

According to Schoonderwaldt the parameters involved in the act of stroking the bow are the speed at which the bow slides on the string, the location of the contact point between the bow and the string, the actual pressure applied and also the tilt angle of the bow; however, according to the research conducted by F. Ablitzer and J. P. Dalmont, the dominant parameters that largely affect the quality of the sound are the speed and the applied pressure.

As Andreas Crohnjort stated in his research, who develop a device that plays the violin, found out that having a mechanical sliding mechanism, the values for the parameters must be kept in within certain limits: the velocity normally is between 40 and 30mm/s, the force(pressure) on the bow is between 0.1 and 3 N, the bow bridge distance is usually between 10 to 60 mm (Askenfelt, 1986).

In the past researchers have built several methods for bowing the violins in a variety of mechanical ways (Saunders et al., 1937).

As stated by D. Young, because of the very shape of the wooden part of the bow, when performing, the pressure has to change according to the contact point between the bow and the string: in fact if the force applied (pressure) is kept steady, the result will be that the middle part of the horsehair will touch the wooden part of the bow, inducing a "dirty" quality of the sound.



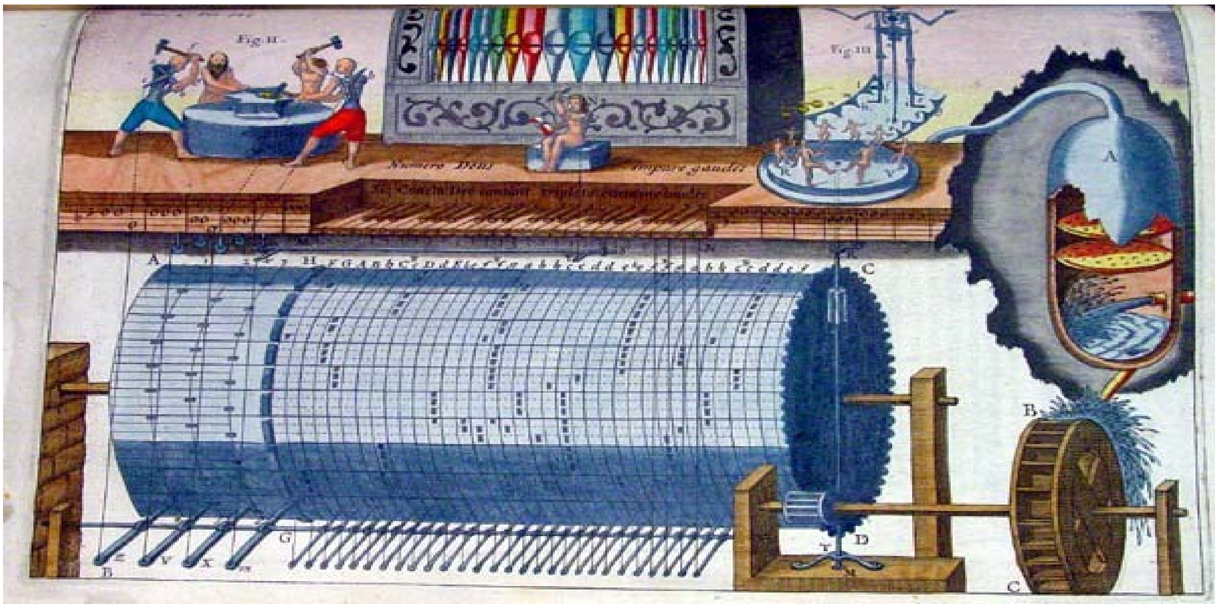
PICTURE 4
The first bow shows the initial state with the steady tension **T** of the horsehair; the following picture involves the force applied **F** and tension **T** of the hair: as you can see, if the applied force overpasses a limit it forces the hair to get in contact with the upper wooden side of the bow; the bottom picture shows that there is an other force acting on the **X** direction(direction of the bowing act): is given by the 2nd Law of Physics: **ma=F**; in this case since the bowing act could be represented with a velocity vector **V**(velocity given by the hand), therefore **a**=first derivative of velocity **V,** then the acting force **F** in on particular direction is given by **F=m(mass of the hand)a(acce leration=first derivative of the V vector**

F. Ablitzera and J.P.Dalmont, 2010/2011

After conducting investigations about the physics behind a bowing process and understood the under laying concepts that characterize the sound quality of the bowing process, as well as studying the different works done by other students and understood the different choices for each concept, t has been concluded that, given the time frame for this project, it is a necessity and priority to follow the simplest concept in terms of design and performance.

As previously mentioned, there have been many attempts in the past to come up with a device that could play the violin and maybe extend it to other members of the string family; obbyists, professionals and artists came up with different approaches but all of them paying attention to the fundamental parameters that regulate the quality sound during a violin performance: speed, applied force and contact point.

The very first example of a fully device that could play string instrument is to be addressed to Athanasius Kircher who first in back 1650s invented a water powered device that transmitted mechanical motion through a water wheel.



PICTURE 5 Music invention by Athanasius Kircher (Morristown, New Jersey , 2013)

In late 1920s, as the technological development advanced, music companies started to launch on the market automated musical devices that incorporate more different instruments. One of these is the Violano Viruoso designed by Mills Novelty Company, Chicago, Illinois (Morristown, New Jersey , 2013).

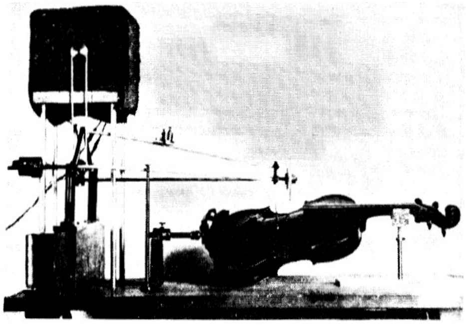
PICTURE 6 Marvel of the early 20th century 1926, Mills Novelty, Morristown, New Jersey , 2013)

You can clearly notice from picture 5 that there are 2 mechanical blocks that dominate: the bowing block and the fingering block.

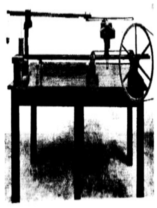
Many students who tried to develop a fingering system, almost all of them came up the same concept which is having something like a particular mechanical part that hits the string, like hammering it. This mechanism is achieved either using servos that activate a lever system that hits on the strings; either using push-type solenoids placed on the top the notes positions.

For the bowing system there are 2 different approaches: some of the researches and students came up with a slider mechanism that would physically slide the bow on the string and at the same time be able to tilt in order to change strings; some others, to overcame the physicality of the bow and actual space that it occupies, they came up with rotating wheels with horsehair that make possible the sound production. Eventually there were 4 wheels, each one on a string, and each with a particular width in order to increase the contact surface: when rotating they act like having a bow that slides; some other devices simply move or rotate a loop made out of horsehair

Recently, a simulation of the bow by such mechanical systems controlled by a software, has proven to be successful in vibrating the string and obtaining an "acceptable" quality of the sound (Weinreich & Caussk, 1986).



PICTURE 7 A bowing machine using a rotating the disc to excite the string (Saunders, 1937).



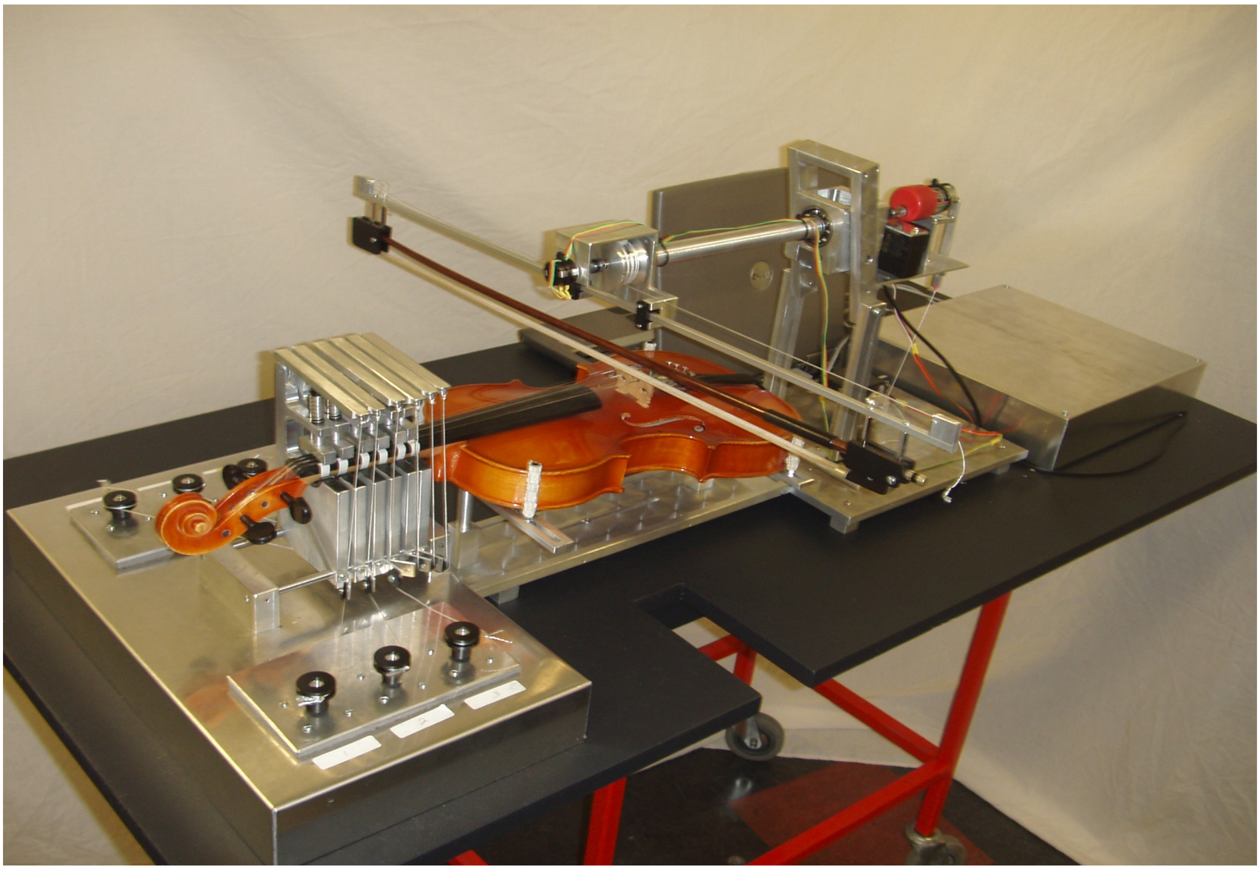
PICTURE 8 A bowing machine using a normal bow to excite the string(Raman, 1920).

A more advanced and accurate approach to build a sophisticated bowing system is addressed to many researches like F.Ablitzer, N.Dauchez, J.P.Dalmont who went deep into the physics behind the bowing process in order to record all the involved forces and physical behaviours. They determined and developed a mathematical model based on the fundamental parameters that characterize the bowing action.

Many other students developed much more accurate algorithms for bowing devices and the results have been adopted successfully into humanoid robots performing autonomously with the violin, like the the Asimo Robot dveloped by Toyota Corporation in Japan.After a long research regarding mainly the material availability and time needed to design and actually assemble a single and sophisticated bowing system, a different approach has been taken: according to Askenfelt,1986, using a mechanical sliding mechanism, given a steady contact point and keeping an average applied force, the sound outcome is acceptable to ear.

Based on this conclusion, a mechanical sliding mechanism is the choice that better fits this project's constrains.

To more support that choice, an inspiration also came from the job done by Y. C. Chia, B. Y. Hong, C. H. Lee, B. K. Lim and F. Wornle who came up with a mechanical sliding system controlled by a motor and a servo: the motor will spin and pull the bow held by a rigid sliding bar which is connected to the shaft of the motor through a rigid wire; the servo will rotate in accordance to the strings positions allowing the change from one string to an other as Picture 8 shows.



PICTURE 9 Fiddler-Robot by Y. C. Chia, B. Y. Hong, C. H. Lee, B. K. Lim and F. Wornle, 2006.

This project is the result of a group of Australian students who actually clearly used a sliding mechanism to obtain an acceptable sound quality: the structure is placed on the back of the violin and from the top there is the sliding bar attached to the rotor that gets the rotation from the motor through a mechanical transmission. The bow is held by the sliding bar and it touches the string in a manner that, when the bow is exactly halfway, the horsehair won't touch the wooden part of the bow itself, eventually causing a dirty sound. After several tests the students ended up with this approach considering the average applied force. From the back, is attached a servo motor that by rotating can move the bow from one string to an other. Since this mechanism turned out to be reliable and mechanically simple to design and build, it has been taken as an example for the next steps.

3. BOWING SYSTEM DESIGN

3.1 ROBOTIC ARM CONCEPT

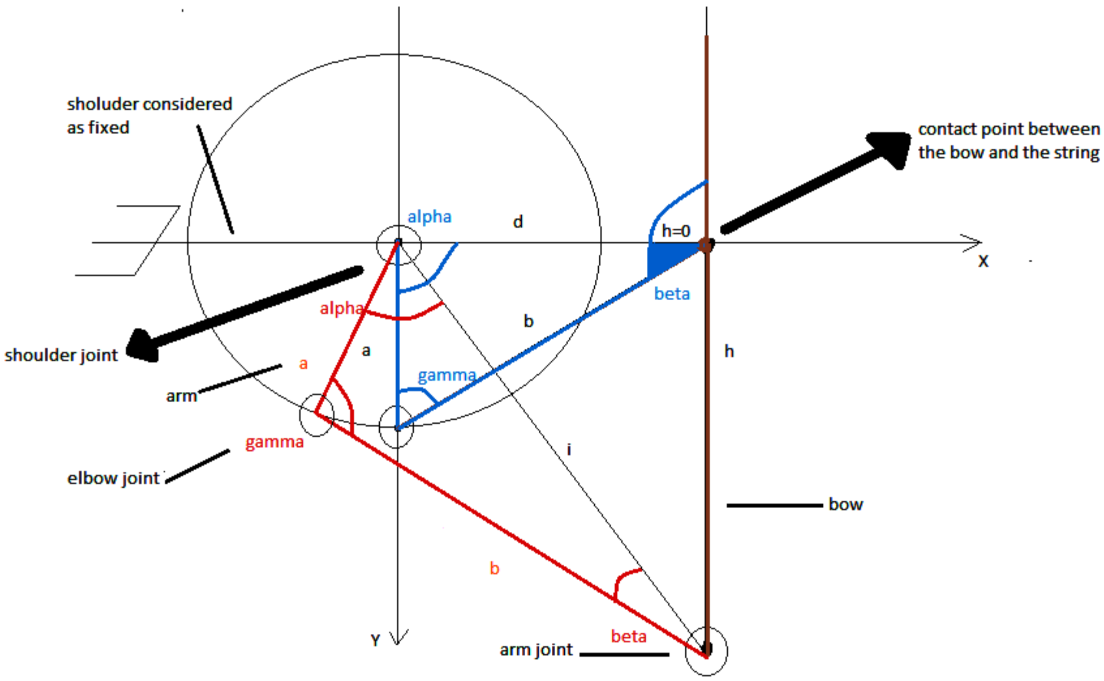
Since the beginning the aim was to develop a robotic mechanism that would be able to coordinate the motion of the bowing with fingering processes. Focusing initially on the bowing mechanism, the idea was to have a robotic arm that would eventually slide the bow along the

strings.
If this configuration could be plotted into a schematic representation, you would have a robotic linkage defined as a sequence of links connected by revolute joints acting on coplanar planes; the links would have been 4 with 3 revolute joints, the shorter link would have represented the shoulder, after the first joint then the arm, the elbow joint, the forearm and its joint and last the hand.
Having this robotic configuration the target would have been to execute a straight motion perpendicular to the string relative to the shoulder. In order to achieve a geometrical algorithm necessary for the kinematics for then expressing it into Arduino Uno language, a trigonometrical representation was simplified.
As a geometrical representation, it is possible to analyse the relation between the angles of the joints following an imaginary straight path. It is assumed that that lengths of the links are known, as well as the distance between the shoulder and the contact point of the bow over the string.
Furthermore, to simplify the calculations the length of the arms, forearm and the distance between shoulder and contact point of the bow, are assumed to be the same.

3.2 GEOMETRICAL ALGORITHM

To analyse the bowing act, it has been considered as first configuration when the tip of the bow (the hand) is on the string (contact point); then as a second configuration when the bow have been slid all the way down stretching the
arm and changing its initial configuration by changing the joints angles.
In the first configuration the length of one side of the triangle is exactly the distance between the shoulder and the contact point which their values are known; then moving on the second configuration to notice is how the distance between the shoulder angle and the hand angle changed (greater). This length also corresponds to the hypotenuse of the triangle given by the shoulder angle, hand angle and contact point; now since the length of the bow changes also the above hypotenuse changes, therefore there is a direct relation between the length of the bow and the configuration of the arm. Since the length of the bow is along the imaginary straight path relative to the contact point, it is possible to determine the length of the hypotenuse as a function of the bow length.
In fact, associating respectively a= arm length, b=elbow length and d=contact point distance relative to the shoulder, l_b=length of the bow, i=hypotenuse of the triangle formed by the d and l_b, it possible to express that relation: considering the first configuration, d=the greater side of the triangle adb; now as the configuration changes i could be always defined as $i=\sqrt{(d^2)+(h^2)}$; at the same time $i=\sqrt{(d^2)+(h^2)}$ is also the side of the triangle abi; therefore, as the the law of sine states, it is

possible to get the relation between each link with its corresponding joint:

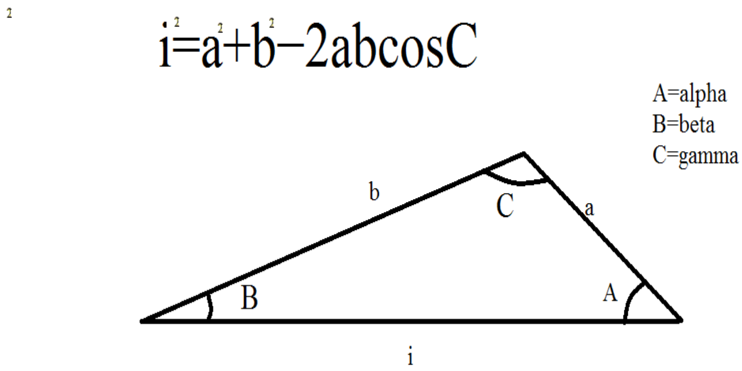


PICTURE 10 Geometrical model of the robotic arm; in blue is described the first configuration and in red the second one. (picture made with PAINT software, 2014)

$$\frac{a}{[\sin(alpha)]}=\frac{b}{[\sin(beta)]}=\frac{c}{[\sin(gamma)]}$$

As the picture shows, the blue lines define the first configuration and the red the second; as you notice the initial length of the hypotenuse is d becoming then I (in black); since a and b don't change therefore here applies the law of sine.

If we combine that definition with the cosine law that states as follow:



PICTURE 11 The cosine law applied to any triangle.

Now, knowing the length a, b and also i as $i=\sqrt{(d^2)+(h^2)}$ and also that $i=\sqrt{(a^2+b^2+2\text{abcos}(C))}$ from the cosine law, it is possible to workout the angle configuration at any value for h within its limit which is the actual length of the bow: here it follows the process done: $\frac{a}{[\sin(alpha)]}=\frac{b}{[\sin(beta)]}=\frac{c}{[\sin(gamma)]}\ sine\ theorem$

$$i^2=(a^2)+(b^2)-2\text{abcos}(beta)\ cosine\ theorem$$

$$cosine\ theorem\ \cos(beta)=\frac{[(a^2)+(b^2)-i^2]}{2\text{ab}}$$

and then if we use the inverse relation of the cosine, we can write as follows:

$$beta=\arccos\frac{[(a^2)+(b^2)-i^2]}{2\text{ab}}$$

Now that we have the value of one angle, in this case the angle beta, we can easily get the other 2 angles by applying the sine law as follows: $\frac{a}{[\sin(alpha)]}=\frac{b}{[\sin(beta)]}$ where beta now is known;

$\sin(alfa)=\frac{(asin(beta))}{b}$ now repeating the same process we have that

$alfa=arcsine[\frac{(asin(beta))}{b}]$ and then for gamma we simply calculate

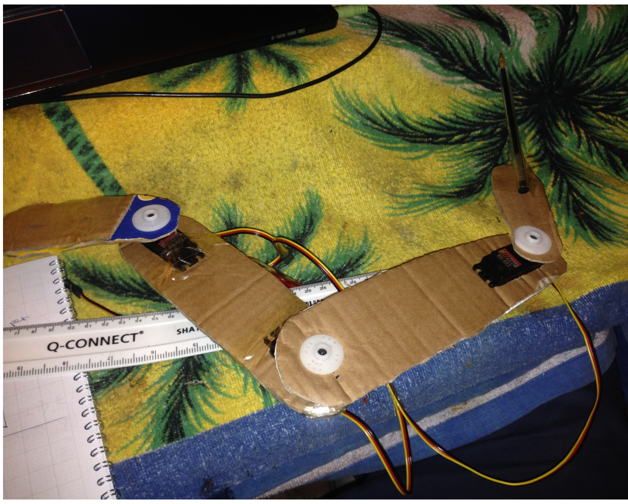
$gamma=pi-(alpha+beta)$ .since the angle summation of a triangle is always equal to Pi=180º.

At this point that all the angles are determined, it was possible then to relate their variation to the variation of the bow length; by doing so it was possible to have control of the bow length through a stepper motor by controlling either the right position either the speed.

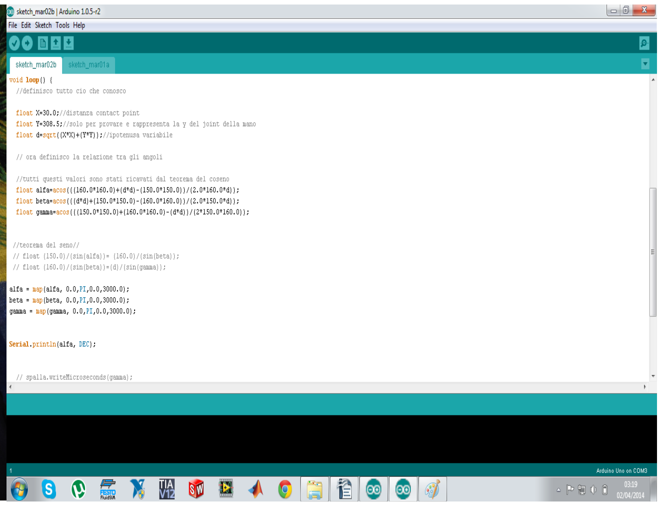
Basically it was possible to change the configuration of the arm, therefore changing all the angles, simply by changing the length of the bow with respect to the contact point.

Before assembling the whole arm a common reference frame has to be chosen carefully for positioning the servos in order allow all the servos to rotate exactly in the same directions, in other terms it is assumed that, since the joints are coplanar, they share the same positive rotation as well as the same negative rotation; furthermore they have been fixed to the links in different positions also to allow a certain "free range of rotation" since the servos run in a range between 0º and 180º.

After doing so, based on this simple trigonometric model, a very simple early-stage prototype have been made out of cardboard and 3 hobby servos to try the actual algorithm. It has been used Arduino Uno and a 9V battery to run the simple model.



PICTURE 12 Robotic arm cardboard prototype



PICTURE 13 Arduino code written to drive the servos by defining just one variable parameter which is the length of the bow again.

4. ARDUINO CODE TEST

- refers to PICTURE 9

#include <Servo.h> this represents the servo library provided by Arduino set of libraries

Servo hand;

Servo elbow; } these instances define servos attached to the hand, elbow and shoulder joints

Servo shoulder;

void setup()

{

Serial.begin(115200); communication speed between Arduino and the servos

shoulder.attach(11);

elbow.attach(10); } indicate the pins used to control each servo

hand.attach(9);

}

void loop() {

//I first define all the physical dimensions that I know and I need which have been mesured.

float X=30.0;//contact point distance which is the distance between the shoulder joint and the bow touching the string (side d)

float Y=308.5;//this is the value for the bow length and it has been chosen this value just for testing purposes   (side h)

float d=sqrt((X*X)+(Y*Y));//variable hypotenuse (side i)

// Here I define the trigonometrical relation between angles

//Cosine law applied $alfa=arcsine[\frac{(asin(beta))}{b}]$; then the same for beta and

float alfa=acos(((160.0*160.0)+(d*d)-(150.0*150.0))/(2.0*160.0*d));

float beta=acos(((d*d)+(150.0*150.0)-(160.0*160.0))/(2.0*150.0*d));

float gamma=Pi - (alfa+beta);

//Sine law

float (150.0)/(sin(alfa))= (160.0)/(sin(beta));

float (160.0)/(sin(beta))=(d)/(sin(gamma));

alfa = map(alfa, 0.0,PI,0.0,3000.0);

beta = map(beta, 0.0,PI,0.0,3000.0);

gamma = map(gamma, 0.0,PI,0.0,3000.0);

shoulder.writeMicroseconds(gamma); // rotate the shoulder angle by gamma value

//delay(10);

elbow.writeMicroseconds(beta); // rotatate the elbow angle by beta value

//delay(10);

hand.writeMicroseconds(alfa); // rotate the hand angle by alfa value

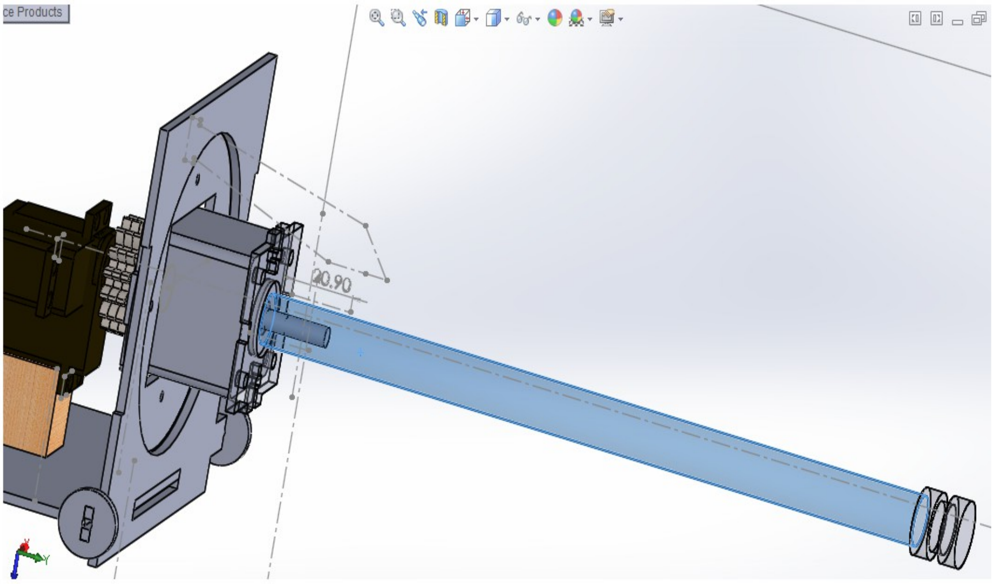
}

After trying successfully the model and considering the fact that if we chose to follow this approach, a simple robotic arm won't reveal to be enough to achieve a smooth and clean sound according to Diana Young, 2001; therefore it will require enough time to figure out the right choice of the material to use, time to chose and test different servo, time to test the most convenient ways of transmitting the joints rotation either by using a system of belts running from servos attached to the arm's base; either by mounting servos right into the joints; it would have required also time to test and determine the balanced values of the fundamental parameters involved in the bowing act such as force applied, speed of the bow and contact point. An additional job to achieve a successful robotic arm that slides correctly the bow along the string, is also the need of an other motor that controls the tilting of the whole shoulder in order to allow the robotic arm to change strings: that means introducing an other degree of freedom into the system, therefore increasing its complexity. An other bunch of time will be necessary to develop a code that coordinates the motion of the bow with the fingering process considering a 4links-3 revolute joints robotic arm with an other rotation for the shoulder. Figuring out the total time needed to develop such system would have required much more time than the actual time available, considering also the time spent developing the overall prototype has been gone. Taking into account the necessity of using the time available to develop a bowing system that could produce an acceptable sound, this approach has been discarded in accordance with the project supervisor professor Martin Smith and a much more simpler approach have been considered.

5. MECHANICAL DESIGN

According to Askenfelt (1986) it is possible to apply a sliding mechanism choosing the right applied pressure.
Taking in consideration that and also observing the job done by B. K. Lim and F. Wornle(2006), a similar approach have been taken; to design and model the mechanical parts of the bowing system, it has been used Solidworks 2013 Student Version.
The idea is to design a very similar structure that holds and slides the bow on the top of the strings.
Following is the design of the first prototype of the "bowing arm" and all the decisions made upon mechanical components realized with Solidworks 2014; the time needed to design and then

assemble the whole structure is 3 days.

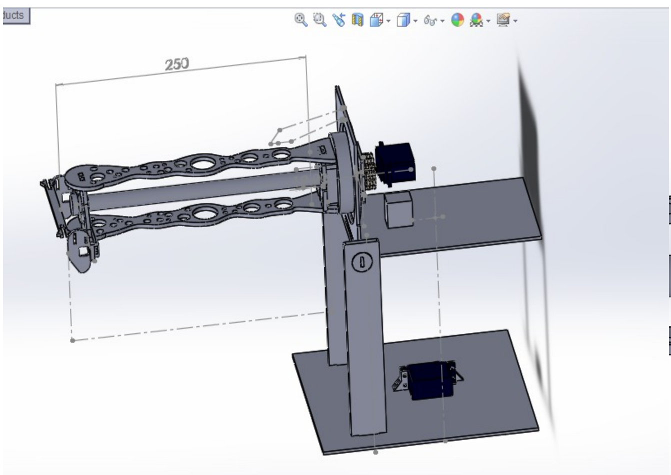


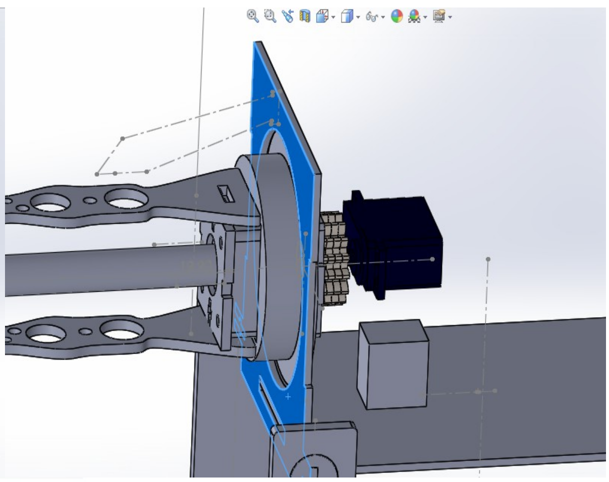
PICTURE 14 Solidwork ,3D model rotor extention attached to the shaft of the stepper mototr

To achieve that, a stepper motor have been chosen because of its good performance in positioning without any particular sensor, therefore controlling the speed and position of the bow; the stepper motor is placed in a box that is free to rotate inside a plate; that box then is connected through a rigid extension which holds the long rotor attached to the shaft of the stepper motor coming out from the box.

From the other side of the box, on the opposite side of the shaft, a servo is attached to the box itself and fixed through the base: rotating will rotate the whole arm with the rotor, therefore changing the position of the bow on different strings.

Then the whole complex described above is attached to 2 stands connected to the ground level and it is free to rotate; on the ground level is fixed a second servo that is connected to the system through a wire in order to control the bow position above the strings.

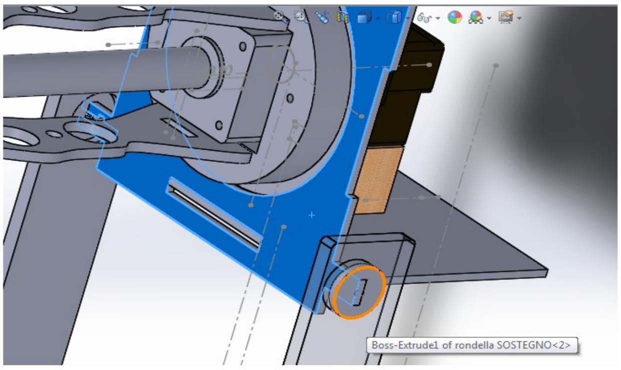




PICTURE 15   3D model of the overall bowing structure and the servo attached to the back of the hosting box

As the pictures show, the dark component represents the servo; to notice that the rotation of the front plate through the stands is achieved by using a wheel with the same material directly fixed to the front plate terminals rather then using ball bearings or any other particular mechanical components with minimal rotational friction.

The same concept has been then adopted to the disc that contains the motor box: the actual disc is free to rotate within a circular cut-out of the front plate; to notice that the disc holds the actual arm at the same time.



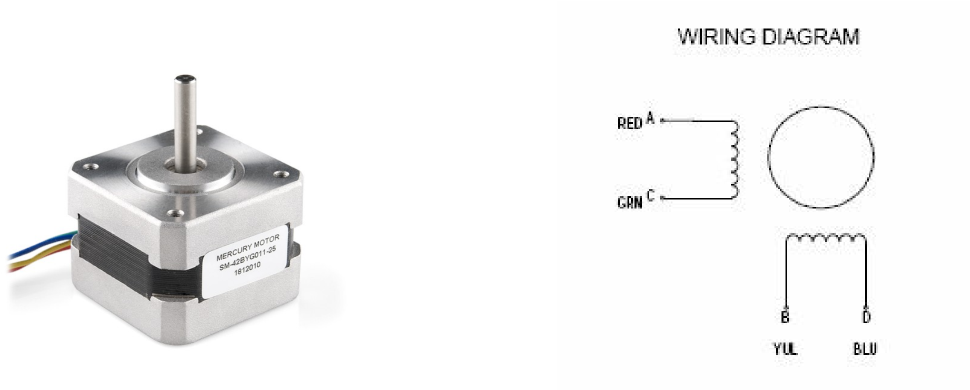
PICTURE 16 In the picture is represented a wheel inside the box with the stepper motor,

Initially the prototype has been printed out onto mdf (Medium-density fibreboard), the cheapest material provided by the Mdx University Shop for prototyping. MDF is a typical engineering prototyping material, which is an end product of softwood fibres residuals, combined with wax and resin binder and then pressed by applying high temperature and high pressure.

Thanks to its density that gives a particular light weight and strength to the material due to the manufacturing process, MDF has all the characteristics to be a good substitute of wood or other more expensive otherwise materials, being stronger and lighter enough.

The density of the mdf varies as the thickness of the samples: the board used for the bowing prototype is a 3mm which is 0.7g/m^3; in its category is a medium dense fibreboard (m-d-f).

Because of its affordable cost and its reliability from previous projects, a 12V bipolar SM-42BYG011-25 stepper motor has been chosen to drive the bow.



PICTURE 17   SM-42BYG011-25 and its wiring diagram (SM-42BYG011-25 online datasheet, 2014)

COMMON RATING		SPECIFICATIONS	
STEP ANGLE	1.8° 5%	VOLTAGE	12V
PHASES	2	CURRENT	0.33A
INSULATION RESISTANCE	100Mohm(500V DC)	INDUCTANCE	46 20% Mh
CLASS OF INSULATION	**B**	RESISTANCE	34+- 10%
WEIGHT	0.20Kg	HOLDING TORQUE	0.23N.M

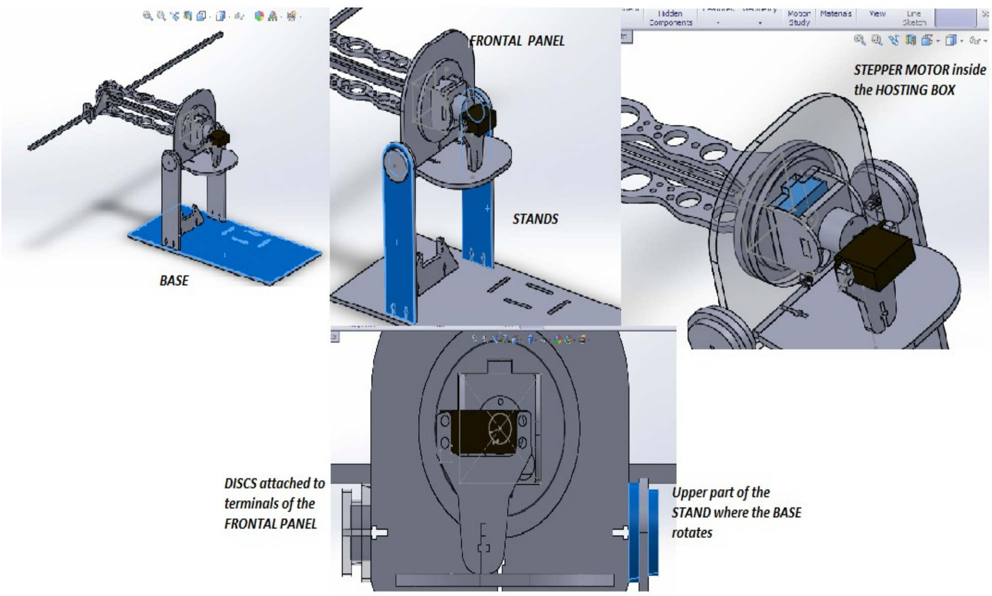
TABLE 1 Technical specifications from SM-42BYG011-25 online datsheet, 2014

Picture 18   First assembled prototype in mdf and the shaft extention in aluminium

After designing and assembling the first bowing mechanism prototype, its functionality has been tested on the violin and confirmed and some little aspects such sizes and particular shapes have been improved into SolidWorks for a second model to print out and assemble.

To drive the stepper motor and the two servos it has been chosen the Adafruit Motorshield V1.1 for its reliability from previous projects and also for its simplicity; the motorshield is designed to be able to drive up to 2 stepper motors, either unipolar or bipolar, up 2 servos with separated pins for external power supply in case the servos require more power than the Arduino can provide; up to 4 bi-directional DC motors; furthermore based on the technical details provided by Adafruit manufacturer, it contains 4 H bridges provided by the L293D chip which can output from 0.6A till a 1.2 A peak per bridge; the motor controllers in this shield have been designed to be powered by 4.5V up to 12V, in fact in the official website of the manufacturer it is clearly specified that common motors or hobby servos usually rated at 1.5V or 3V won't run.

In this project application, the 42BYG011-25 stepper motor requires 0.33A at 12V so it is fully compatible to be driven by the motorshield that will be powered by a 12V Lead Acid battery; the 2 servos used in this project are hobby-servos which are rated at 4.8V to 6V and they require a minimum of 8mA up to 150mA when a load is applied, therefore since both of them will be used to drive a particular load, they will use the 40mA from the microcontroller; the Arduino power supply can be either from the usb cable or from a 9V battery.



PICTURE 19 3D model showing showing how is obtained the rotation of the stands achieved without any use of ball bearings.

Firstly the base was designed just as a plate to be connected to the stands; in the second prototype it has been extended in a way that could host the 12V 1.2Ah Lead Acid battery chosen having a base of 97x44mm; it also has space for a strip-board containing the circuitry for the solenoids having size 22x85 mm; it also includes enough space to host the Arduino board.
The final size chosen in the second prototype for the base is 200x411mm.
The stands have a length of 236mm and it has been chosen this value because it is the minimum required to keep a "safe" distance between the bow and the strings of the violin when the overall structure is in in place, then that distance can be regulated by the servo placed at the base; to connect the frontal panel with the stands, 2 extensions from the panel have been designed that fit right inside a series of discs: firstly a large disc having radius=30mm then a smaller one having radius=25mm; the size of that second disc is exactly the size of the circular cut out on the stands resulting in a rotation between the front panel and the stand itself.
Attached to the panel there is a plate which hosts a stand that holds in place a first servo motor attached to the stepper motor box.
The length of the aluminium rotor extension is 265 mm and it is exactly the distance from the back of the violin to the contact point of the bow which is at 10mm from the bridge.

5.1 THE BOW-HOLDER

As has been described at the beginning, the bow is attached to a bar that slides through 2 slots parallel to each other to ensure the straight motion of the bar; the bar is then connected to the rotor head through a wire that is fixed in both extremes of the sliding bar. The wire has also been fixed to rotor head so that each time the wire wounds, the bar is pulled by the winding. It is a simple mechanism that transforms rotational motion into straight motion.

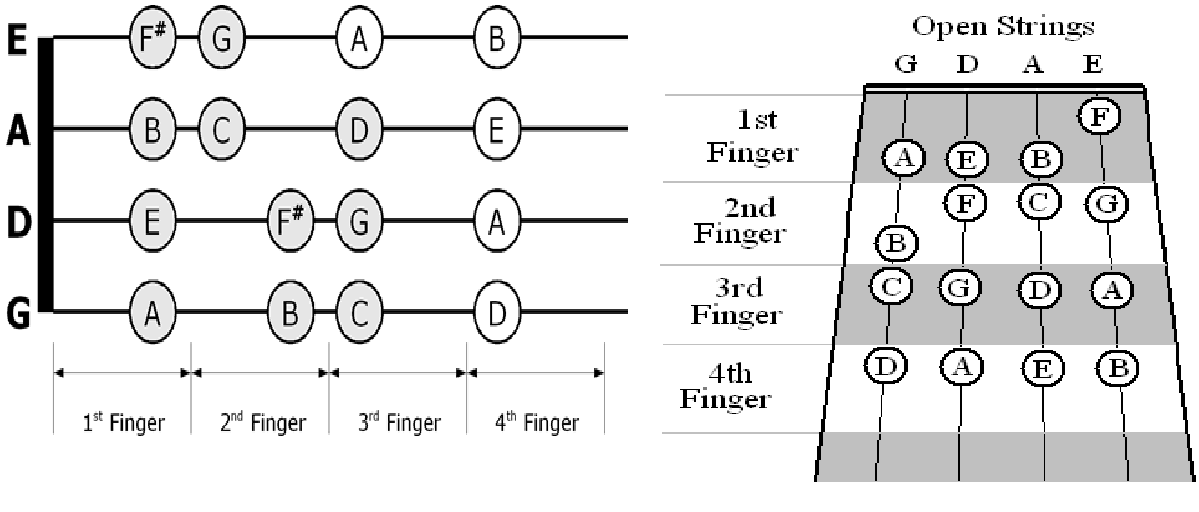
PICTURE 20 Image of the last prototype of the bowing system in acrylic where the wooden part of the bow is attached to the sliding bar through 2 small connectors placed at the tip and frog of the bow

To connect the bow to the rotor it has been designed an acrylic stick with 615mm in length which corresponds to the distance between the tip of the bow and frog, which is at the opposite end. Attached to that stick there are the pieces that really do the job of holding physically the bow: they have been designed with a "U shape" cut-out in order to fit tightly on the wooden part of the bow. The over all structure is designed considering a thickness of 6mm of acrylic sheet. It has been chosen to use acrylic because of its more professional look rather than mdf, and since there was no availability of 6mm acrylic sheets in the workshop provided by Middlesex University, it has been decided to use 2 layers of 3mm .
To hold and fix the over all a standard metallic M3 20mm bolted screws with 6mm bolts have been used.

5.2 FINGERING SYSTEM

Looking at different examples and different concepts for the fingering process adopted for a violin, it emerged that the majority of who have tried so, used a system that consists of a lever mechanism triggered either by servo motors either by push type solenoids.
However this approach has a great physical impact on the over all looking of the violin device since you would need a physical lever for each note.
The advantage of this method is that one lever pushes down all the 4 strings simultaneously and, as the picture 18 shows, the only thing to do then is play on the right string: in fact as you can notice there are common finger positions through all strings.
Observing the fingerboard of the violin you can notice the distance between strings increases as you

move along the fingerboard toward the bridge. An other important aspect to be mentioned is that the first note of the first octave of the E string is physically too close to the tip of the fingerboard and also the distances between strings in that particular point where the note is located, became relatively smaller.
This particular physical configuration of the violin probably is one of the causes that represents an obstacle to develop a fingering mechanism using push type solenoids.
At a more advanced stage companies like Toyota Corporation developed a humanoid robot able to smoothly play the violin using an actual robotic hand that is based on algorithms with a much more higher complexity.
To develop a testing system, a push type solenoids approach have taken in consideration.
The aim is to be able to have a configuration of solenoids that would eventually push over the string and covering a range of a full octave on each string , which in reality corresponds of using all the 4 left fingers on the fingerboard. To achieve that the idea was to place a set of solenoids into the common position to all strings as the picture shows.

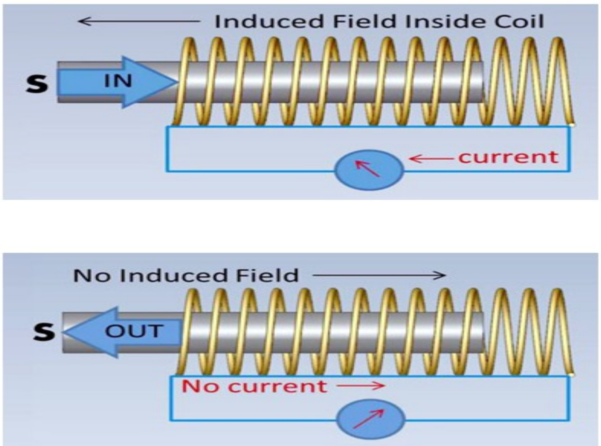


PICTURE 21Schematics representing the positions of the 4 fingers over the 4 strings

As you can see the positions of the finger #3 and #4 are common to all strings as well as the positions of the finger #1 and finger #2 which are respectively common to the first 3 strings starting from string G, and the other common to the last 3 strings relative to string G.
It is important to mention that this pattern of the positions it is not fixed as you move along the fingerboard: it does change in all octaves. Therefore it is not possible to have a sliding set of solenoids that eventually would have been sliding along the fingerboard; that explains why the majority of the projects relative to this instrument, adopted a fixed lever system for the fingering.

It have been decided to develop a fixed set of solenoids that would trigger just the notes needed for the execution positioned exactly right on the top of the note location on the fingerboard; to reduce the amount of solenoids, it have been decided that eventually each solenoid would be positioned in a way that hits 2 strings simultaneously, then by tilting the bow you can choose which string to use.
It has been chosen a push type solenoid with the following technical specifications: DC 12V, 500mA and it is an open frame push type solenoid with 7mm Stroke.
By "open frame", means that the core and the actual coil are mounted inside a metallic box structure with 2 open sides so the coil is visible to the user.
It has been chosen this particular solenoid mainly for its dimensions: in fact in order to design a set of solenoids over the notes positions, all solenoids used had to be physically within the width of the fingerboard. This particular one is an open frame solenoid having size 2cm x 1.6cm x 1.3cm / 0.8"x 0.6" x 0.5" (L*W*H); 2 of those next to each other fit just rightly on the position of the first note; this is also the reason why it has been decided to push 2 strings at the same time using just 1 solenoid.

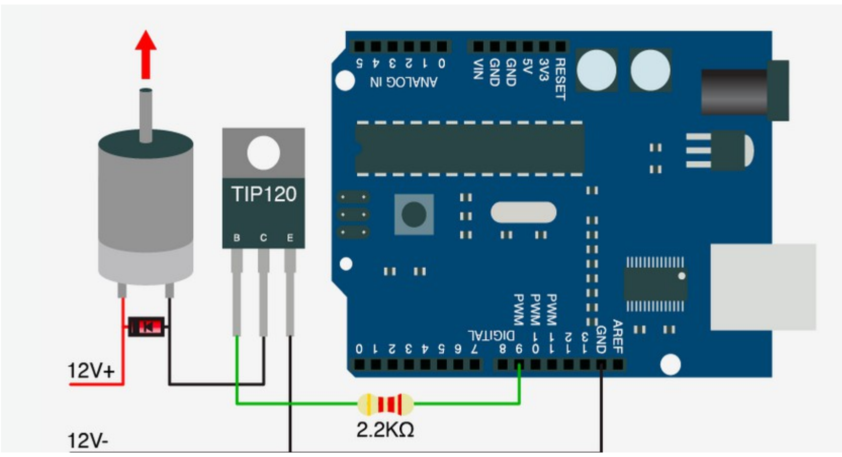
PICTURE 22   500mA Open Frame Push Type Solenoid



PICTURE 23 Here are the illustrations explaining the induced current caused by the change of the magnetic flux during the act of retracting back of the core inside the coil of solenoid with the magnetic flux in order to generate mechanical motion.

Usually solenoids are made of a copper coil that when energized acts strongly on an iron or steel core; being possible to control current flow, it is possible therefore to control the mechanism: in fact when current flows through the copper coil it generates a magnetic field which intensity is proportional to current intensity. However it is not possible to control speed or position of the stroke because of the natural magnetism properties. Push type solenoids in general have a spring that retracts back the metallic core to its initial position when the coil is d-energized. This action of retracting back the stroke, has a particular implication on the circuitry that is going to be connected with.
In fact when the metallic core retracts, it induces current through the coil that would eventually flow

out from the terminals of the the coil: this effect is known in physics as electromagnetic inductance. In this particular case, since the fingering solenoids would be powered by Arduino, a carefully design circuitry has been made: to avoid the back flow of induced current to Arduino which eventually would be destructive for the microprocessor, it has been utilized a diode.
Diodes have the particular function to allow current flow in just one direction: that is achieved thanks to the chimical-physical properties of the material used to manufacture the diode itself.
An other component necessary to control the solenoid through Arduino, is a transistor that would act as a switch. The implementation of the transistor is necessary because an Arduino can output only 3.3V or 5 V and the solenoid needs 12V and a much higher current than the microprocessor would provide which is 40mA per pin. As the following schematics show, the signal from Arduino through the base, would trigger the current flow from collector(Power supply) to the emitter(to the coil).
The TIP120 is an NPN Darlington transistor which is designed with an Emitter-Base Voltage of 5V and the Base-Current of 120mA peak based on the informations from the datasheet.



PICTURE 24 Arduino schematics for a solenoid using a TIP120 transistor

Arduino Uno is a microprocessor that get powered by 5V either by the USB cable plugged to the hosting pc where the voltage provided is regulated at 5V directly from the computer, or by an external source such a 9V battery; there is also a 3.3V pin on the board for particular applications. The current intensity from Arduino's pins is rated at 40mA which is also the amount of current that pins can take when used as inputs.
Since the above described solenoid is rated at 12V 500mA, Arduino Uno doesn't provide enough current to activate the electromagnet, therefore an external power source is necessary. For testing

purposes it has been used a power generator which provides a much more power supply flexibility. Before using the power generator, a very first test by a 9V battery revealed an important issue: the battery used provides 225mA and that current is more than enough to energize the coil and activate the pushing mechanism, but the pressure applied is not great enough to hold the string once pushed; this is because of the tension of the string which is greater than the solenoid pushing force. In fact, after several tests even replacing the battery with brand new ones having the same rate, it resulted that the pushing force given by 225mA is not great enough to overcome the tension of the string when it is excited by the bow.

During the following test, the amperage has been raised to 500mA by connecting two 9V batteries in parallel with the same Amperage giving out exactly 500mA at 9V. Repeating the same test, revealed that the force provided by 500mA,the rate at which the solenoid has been designed from the manufacturer, pushes the string right against the fingerboard and keeps pressing also when that string was vibrating overcoming the actual vibrational forces and the tension of the string as well. After successfully testing several times with the same current rating, it has been confirmed that 500mA will be the minimum current amount to be set into the power generator at 12V.

An other aspect to be mentioned is that the solenoids , after repetitive tests, get very hot, enough to affect the magnetic strength that activate the stroke and eventually not being able to hold the stroke with the same intensity.

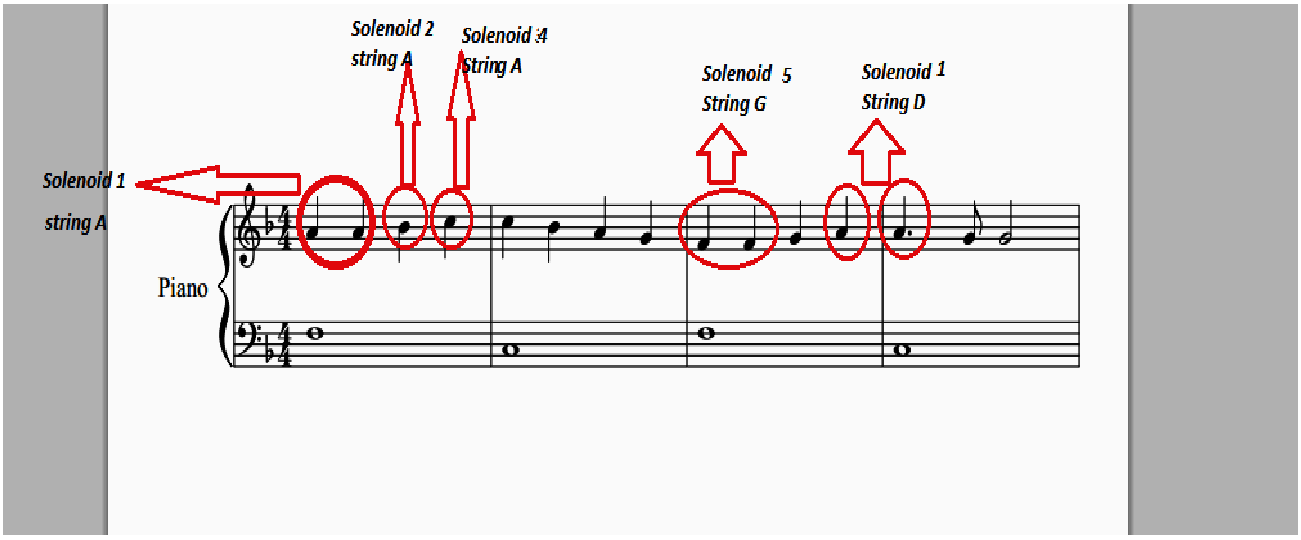
After trying to reduce the I to 400mA with the power generator, the same effects occurred with the solenoids getting very hot and loosing their strength.

Reducing even more to 300mA gave the same result, but this time even before the solenoids get hot, the pressure of the stroke was not enough to push properly the string against the fingerboard.

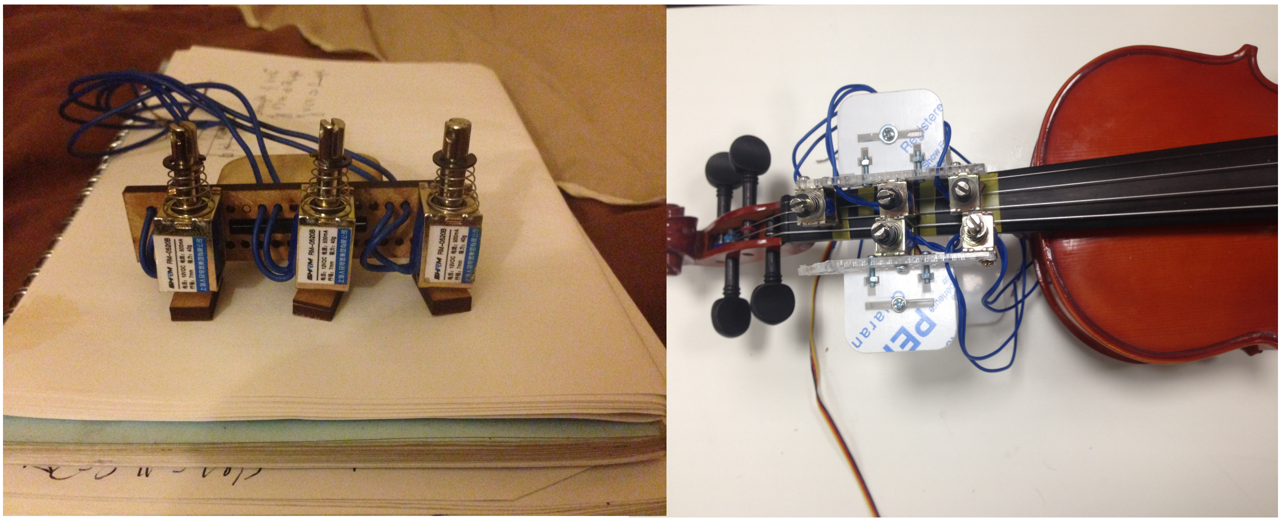
Repeating the same test with the Voltage and Current values set to 500mA into the power generator, the solenoid successfully pushed the string against the fingerboard even while playing a generic note.

For testing purposes it has been considered a fragment of the refrain from the famous Ode to joy composed by Beethoven: this is because of the simplicity of the scale of notes used which can be easily replicated by placing a solenoid for each note, and in this case Beethoven used just 5 notes with 4 fingers in addition to the free strings notes.

It has been decided to use 5 solenoids for the fingering mechanism; considering the Picture 18 above, the solenoids are placed in the following way: Solenoid 1 corresponds to the 1st finger over string A and E; Solenoid 2 corresponds to the 2nd finger over the same strings and Solenoid 3 will be the 3rd finger; Solenoid 4 will be 2nd finger over strings G and D and Solenoid 5 will correspond to the 3rd finger over the same string again G and D.



Picture 25 Relation notes-solenoids



Picture 26 Set of the first 3 solenoids pushing on strings A and E; on the right the whole fingering system placed over the fingerboard; the distances between one solenoid and the other are relative to the notes placed on the fingerboard.

To be activated by Arduino, each solenoid had to follow the schematics above in Picture 21; for this purpose 5 TIP120 Darlington NPN transistors were needed, as well as 5 diodes and 2.2k resistors in the same amount; then the schematics have been replicated for 5 times into a prototype circuit with a strip-board.

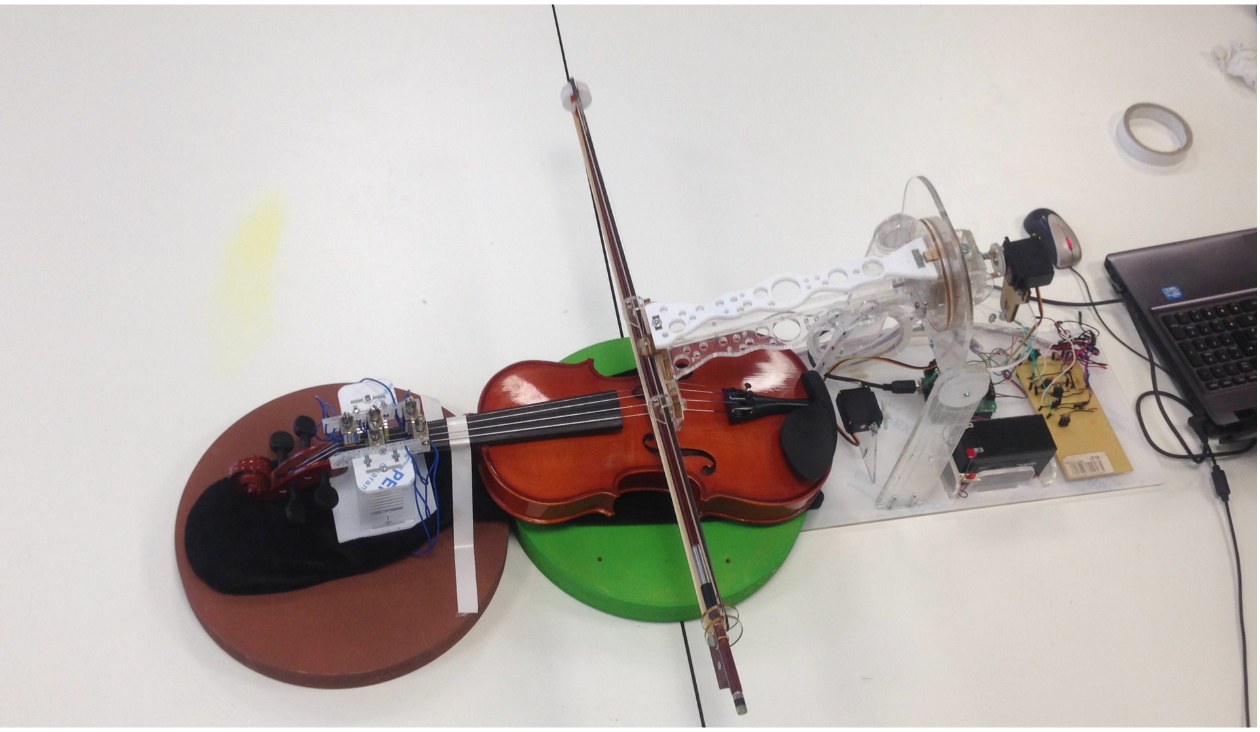
The TIP120 has three pins. One is called Base, which we will connect to any of the Arduino pins. In this circuit the TIP120 transistor acts exactly as a switch: it takes the 40mA signal from a digital pin and through the base allows the the current flow from the Collector to the emitter from the

external 12 V battery.
To control the solenoids directly from the microprocessor 5 pins have been soldered on the motorshield because there was no access to the actual Arduino pins since they have been all used when the motorshield has been plugged into the microprocessor board; the pins used to control the solenoids are 9 to 13; an additional pin to solder was required for the common ground for the solenoids.

6. RESULTS and CONCLUSION

Once the over all structure have been assembled and placed over the violin, a very first test revealed a visible and considerable instability of the structure: when the bow is sliding and at the same time the servo responsible of tilting the bow is activated, the mechanism started to shake visibly affecting the quality of the sound produced; this is toughth to be because of the connection through the nylon wire between the servo at the bottom plate and the rotating plate containing the stepper motor; this issue can be thought to be solved by replacing the actual nylon wire with a rigid connection or with a connection made out of any non flexible material.
An other issue encountered during the testing processes was to fix the violin in such a way that contact surface of the horsehair is perpendicular to the string: by doing so, according to Askenfelt, A. (1986) would result in a full and clear sound; to obtain this configuration the violin had to be positioned with its neck sitting in higher position than the level where its back is sitting on; tests have been done to check how the pressure on the bow would affect the sound and the 2nd HS 422 servo responsible for pulling the arm in order to change the level of the bow over the string revealed to work as expected; however it is still possible to improve the accuracy of positioning by improving the accuracy in controlling the servo since the Arduino library provides a microsteppeing control function to drive a servo. It is strongly adviced to develop further tests adopting servos with higher torque since the HS 422 is a hobby-servo and it is rated at 6V max draining 8mA without any load applied up to 150mA considering a load; in this particular case Arduino Uno provides a maximum of 40mA which gives a limitation of the performance of the servos. During the tests the servos have been always powered by the 5V provided by the microcontroller; however it is still an option to use an external power supply for them in order to obtain a higher torque and so be able to conduct tests with maximum performance of the HS 422servos.
Regarding the fingering mechanism it is important to mention that tests have been conducted using little tiny pushing blocks of mdf attached to the solenoid in order to push the string against the

fingerboard; according to D.Young, the pressing force applied with finger, changes the timbre of the note, therefore also the material used when in contact with string causes the change of the timbre.
It is strongly raccomended to conduct tests using other material, like soft and dense material such as the felt; as stated by Jacubus Steiner, a dumping material such as the felt could play a vital role over the tonality of the note.
Although the complexity of the instrument, it is still possible to programme such a device in order to synchronise the fingering with bowing action and to get a clear sound acceptable to hear, exactly as Askenfelt(1986) has predicted and stated. However some minimal issues can be avoided for example the choice of much more powerful motor and servos would clearly increase the performance of the device; an other issue that strongly affects the performance is the stability of the overall structure, therefore it is raccomended to chose a robust and light material as could be the aluminium.



PICTURE27 Final assembled prototype mounted on the violin.

7. REFERENCES

1. Stepanek, J. and Otcenasek, Z. (2005). Acoustical correlates of the main features of violin timbre perception. spectrum using psychoacoustics experiments. In *Proceedings of the Conference on Interdisciplinary Musicology*, Montreal, Canada.

2. J. Solis, A. Takanishi, and K. Hashimoto, *Development of an Anthropomorphic Saxophone Playing Robot, Advances in Soft Computing*, Volume 83, 175-186 (2010)

3. Nicoleta Bocan25] Katsuhisa Furuta , "Control of Pendulum: From Super Mechano-System to Human Adaptive Mechatronics", *Proceedings of the 42nd IEEE Conference on Decision and Control*, pp.1498-1507, Maui, Hawaii USA, December 2003.

4. Nicoleta Bocan25] Katsuhisa Furuta , *Control of Pendulum: From Super Mechano-System to Human Adaptive Mechatronics*, *Proceedings of the 42nd IEEE Conference on Decision and Control*, pp.1498-1507, Maui, Hawaii USA, December 2003.

5. Nicoleta BocanK. Kurihara, S. Suzuki, F. Harashima and K. Furuta, *Human Adaptive Mechatronics(HAM) for Haptic System*, in proc. of the 30th Annual Conference of the IEEE Industrial Electronics Society(IECON'04), Busan, Korea, in CD-ROM, 2004.

6. Askenfelt, A. (1986): *Measurement of bow motion and bow force in violin playing*,].Acoust.Soc.Am. 80, pp. 1007-1015.

7. Askenfelt, A. (1992): *Properties of violin bows*, pp. 27-30 in Proc. of International Symposium on Musical Acoustics (ISMA '92), Tokyo.

8. Coates, S.R., Higgs, S.J.R., Parsons, L.J., & Townsend, P.D. (1975): *Analysis of tones from automatically bowed violins*, Catgut Acousf.Soc. Newsletter No. 24, pp. 16-17.

9. Lawergren, B. (1980): *On the motion of bowed violin strings*, Acusticn 44, pp. 195-206.

10. Saunders, F.A. (1937): *The mechanical action of violins*, J.Acoust.Soc.Arn. **9,** pp. 81-98.

11. Schelleng, J.C. (1973), *The Bowed String and the Player*, *J. Acoust. Soc. Amer.,* **53**, pp. 26-41.

12. Woodhouse, J. and Galluzzo, P.M. (2004),*The Bowed String as We Know it Today*, *Acustica—Acta Acustica*, **90**pp. 579-589.

13. Galluzzo, P. (2004), *On the Playability ofStringed Instruments*, Doctoral dissertation,University of Cambridge.

14. Smith, J.H. and Woodhouse, J. (2000), *The Tribology of Rosin, J. Mech. Phys. Solids*, **48**, pp. 1633-1681.

15. S. Serafin, *The sound of friction: real-time models, playability and musical applications,* Ph.D. dissertation, CCRMA, Standford University, 2004.