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PRELIMINARY INVESTIGATION ON UNDAMPED OPEN LOOP CONTROL OF A POLISHING JIG FOR MACHINING CENTRES

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Abstract: *In finishing of surfaces with variable curvature the normal force must vary to control contact pressure. In this work, a special jig that provided passive control when used on machining centers was redesigned in order to support active force control. This was achieved indirectly by controlling displacement of the spring – loaded finishing tool by means of a stepper motor and a lead screw. An open loop control system was implemented through a microcontroller and a stepper motor driver. In order to synchronize the movement of the tool along its trajectory with the spring displacement as appropriate, the necessary communication between the microcontroller and the CNC controller was implemented through a serial port. No damping has been used initially in order to investigate adequacy of friction forces to dampen oscillations. Experiments were carried out on a steel flat surface on a 3 axis machining center with different tools and polishing paste grit sizes. Experiments proved the ability of the open loop controller to follow desirable force variation patterns or two different types, namely random and sinusoidal / periodic. In both cases the mean force variation was close enough to the intended nominal one, but strong force deviations were present pointing to the need to use external damping.*

Key words: *Polishing, Active Force Control, Machining Center, Polishing Jig.*

1. INTRODUCTION

Surface finishing has been gaining importance in recent years, given the ever increasing needs for high precision manufacturing and engineering. Regarding finishing techniques for metals, most commonly these are divided into three major categories: grinding, lapping / fine-lapping, and polishing / buffing [1, 2]. Grinding is characterized by fast material removal rates to remove large surface imperfections. Abrasives such as stones, files, emery cloths, belts and discs, usually with large grain size (> 40 μm) are used. During the lapping process, the imperfections remaining from grinding are removed and surfaces of high dimensional precision are produced with roughness typically below 2.5 μm. The abrasives have a small grain size (5–20 μm) and may be attached to emery cloths or be suspended freely in paste form (slurry). Metal tools (e.g. brass), or, for greater accuracy, plastic or wooden tools are used (fine-lapping). Polishing / buffing is the ultimate finishing process. Mechanically it is similar to lapping, but the grain sizes selected are much smaller (3 μm and below). Very soft carriers are used for its execution (e.g. cloth, felt, cotton) producing 'mirror' surfaces with roughness values of the order of 0.01 μm.

Manual finishing is often practiced but it suffers from inconsistency of surface quality and long process duration. As a solution, automated finishing has been advocated on dedicated machine tools [3] or robots holding finishing tools [4]. In both cases, force or pressure control is of paramount importance [5]. Force is actually one of the main control parameters of the process along with tool feed rate, finishing time and paste concentration, if used [6]. Uniform material removal control is based on maintaining a constant speed and surface pressure, thus controlling the force depending on the contact surface between the abrasive tool and the workpiece surface [7]. In addition, different toolpaths and patterns have been examined to provide uniformity of surface coverage [8] [9], with particular emphasis on trochoid curves simulating manual motion exerted by experienced workers [7].

Force can be controlled indirectly through displacement provided that compliance is known [10], or directly by using dedicated sensors [11, 12]. In [4], position / force was controlled based on CAD / CAM systems that simultaneously controls the finishing force and the feed of the finishing tool with real-time feedback. A PID controller has been used in [11] with pneumatic actuators on parallel robots to keep the surface pressure constant. Its extension [13] exploited a compliant tool head and a minimum degree pole placement method is applied to design a self-adjusting adaptive controller. A special case of a PID controller called a Fractional Order $PI^{\lambda} D^{\mu}$ was used for force control in [14].

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A finishing head for robots has been developed in [15] where unlike other cases force control and the motion control of the tool are disconnected.

Passive force control based on tool compliance and algorithmic calculation of tool position and orientation was employed in [12] in the context of mould polishing on 5-axis machining centres. A robotic polishing platform presented in [16] uses "compliance control" to control force based on known elasticity constants of the tool and real time force feedback. Polishing on a 2-axis turning centre was based on a hybrid model to control tool movement and polishing force. Position and orientation of the tool are adjusted to reduce force perturbations [17]. Polishing force control in [18] was not based on any force sensor but on a disturbance observer of the tool speed in addition to a learning processes recording dynamic data from experienced craftsmen.

As a baseline of this work, a methodology for automated polishing of metal surfaces had been determined, the construction of a trochoidal polishing track had been studied, a passive device based exclusively on springs for a machining center had been constructed and optimization experiments had been performed for achieving desired roughness on flat surface finishing [3, 10, 19]. As a result, it emerged that when the curvature of the surface is constant the force will also be kept constant due means of the tool suspension on springs. However, when the curvature or inclination of the surface changes, as typically happens in molds, active force control should be implemented by suitably modifying the polishing jig to embed motorized displacement of the suspension springs, as advocated in this paper.

In Section 2 next the new jig is introduced. Section 3 discusses force control concepts. Section 4 describes the hardware for implementing open loop control and Section 5 presents the pertinent validation experiments performed and Section 6 the results obtained. Section 7 points to conclusions and further work.

2. ACTIVE POLISHING JIG

The existing jig corresponding to passive force control [10] is shown in Fig. 1,*a*. The new design corresponding to active force control is shown in Fig. 1,*b* and its implementation mounted on the machine tool is shown in Fig. 1,*c*.

The new jig accommodates a stepper motor that imparts motion to a middle moving plate via a flexible coupling, a lead screw (of diameter 10 mm and pitch 2 mm) and a brass nut that is fixed on the plate. Two pairs of linear sliding bearings ensure very smooth movement of the middle plate. Thus, the distance of the spring loaded bottom plate from the middle plate varies and so does the polishing force. Note that the polishing tool is fixed on the bottom plate. The condition for no sliding down of the load on the lead screw is fulfilled, i.e. $\mu > \tan \lambda$, where μ is the steel friction coefficient and λ is the lead angle. In this case, $\mu > 0.16$ for lubricated surfaces and $\mu > 0.55$ for dry contact, whereas $\lambda \simeq \tan\lambda = 0.0707$. Due to the miniscule loads there was no need to perform any strength of materials calculations.

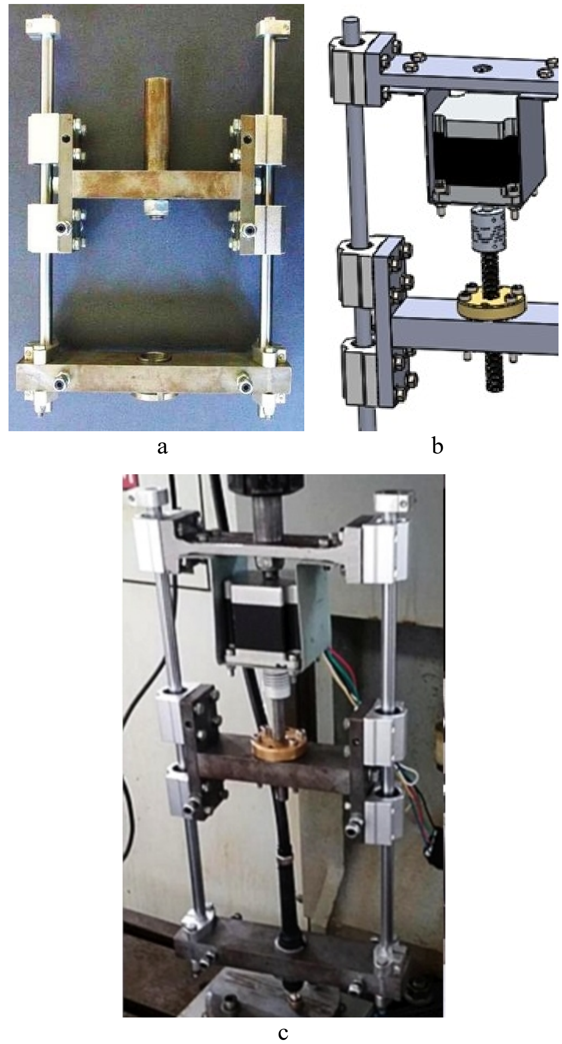


Fig. 1. Polishing jig: *a* – passive used as baseline; *b* – active as designed; *c* – active as installed.

The upper plate is assembled with the two guides using two linear bearings SC10UU providing tight clearance and thus an accurate sliding movement. Two stopper brackets were placed at the upper ends of the two guides; these are needed when the machine spindle lifts the jig.

3. OPEN LOOP FORCE CONTROL CONCEPT

Trajectory is discretized by a number of points. As soon as the tool passes through one of these points, the value of the force corresponding to the next point is retrieved. First, from the value of the force read by the microcontroller, the corresponding value of the displacement of the springs from the following relation is calculated.

$$F = W - (K_T x + F_i), \quad (1)$$

where K_T is the total spring constant, x – relative movement with respect to initial position, W – weight of the suspended part of the jig, F_i – initial force of the springs.

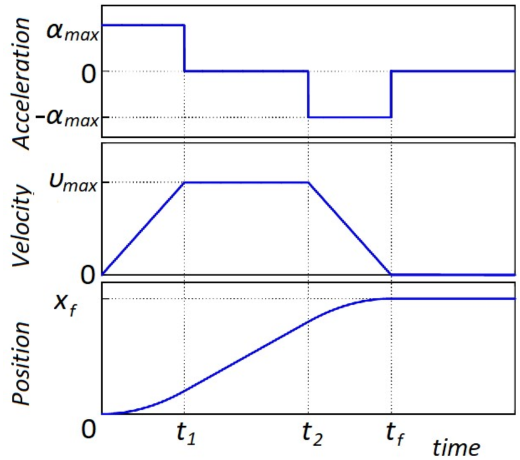


Fig. 2. Typical trapezoidal velocity profile and corresponding position and acceleration profiles.

Stepper motor motion to reach the desired force value starts at the same time with the tool motion to the next point of the path. The end of these two motions must be synchronized. Trapezoidal motor speed profiles were used with a maximum value (600 steps/sec in this case) ensuring both fast movement and no loss of steps, see Fig. 2.

Thus, motor acceleration value is calculated as follows. The tool travels a linear distance *S* with feed f taking time equal to that required by the stepper motor to move so that the desired force value is reached. Thus:

$$\frac{S}{f} = t_b \frac{v_{max}}{a} + \frac{x}{a t_b}, \tag{2}$$

where α is acceleration/decceleration and t_b – the time needed to reach maximum motor speed υ_{max}, typically equal to υ_{max}/α.

However, there are cases in which the motor will not reach its maximum speed, because the travel may be short. In such cases, a triangular rather than trapezoidal motor speed profile is produced, consisting only of an accelerating and a decelerating section. This happens if:

$$t_b \geq S/2f, \tag{3}$$

in which case feed motion duration is:

$$\sqrt{4x/a}. \tag{4}$$

The above calculations are performed in real time by the microcontroller. Note that the delay associated with sending the force value to the microcontroller and making the necessary calculations before the stepper motor starts is not taken into account, as it typically lasts some ms.

4. CONTROL IMPLEMENTATION

The components making up the jig polishing control system are shown in Fig. 3.

The system comprises a Wantai™ NEMA23 57BYGH420 stepper motor of monopolar type with 1.8° step angle delivering a torque of 9 kg·cm at 2 A and 12 V. The Big Easy Driver™ was used for driving the motor, which is based on IC A4988 using PWM to control the mean current delivered to stator windings. No micro-stepping was necessary; by contrast full stepping allowed higher acceleration and speeds. Input voltage is 8 V to 30 V and there is an inbuilt voltage regulator 5 V/3.3 V, allowing the use of a single power supply for the system at 12 V.

The driver is connected to an Arduino UNO™ microcontroller working at 16 MHz which sends to it stepping pulses and direction reversal signals as required. In order to calculate how many such pulses should be sent to the driver at any point along the tool trajectory, the microcontroller needs to be connected to the CNC controller to obtain the current tool position. For each tool position the required force is known, usually having been calculated off-line by a suitable model taking into account the contact area between tool and workpiece. Thus, this value has to be translated into the required rotation of the motor and corresponding displacement of the middle plate that creates the corresponding polishing force. This signal has to be sent early enough, to allow for some delay in the response of the system. Connection of the microcontroller and the CNC machine controller is implemented via an RS-232 interface which all CNC control units possess at ±12 V. therefore, a suitable serial port converter to TTL voltage is required, based on IC MAX3232 and operating at 3.3 V. To achieve the desired communication the Arduino™ SoftwareSerial library was used to map two digital ports in serial (Rx / Tx).

Data is sent through the RS-232 serial port on the machine side with the help of macros, peculiar to each machine controller manufacturer. These are essentially routines or subroutines that contain non-G code commands and make use of variables (corresponding addresses). For example, the macro command DPRNT of the Haas™ machining centers sends data to text files, but also to other external devices. Specifically, the G code used for polishing trajectory stores the desired values of the forces in variables, depending on the position of

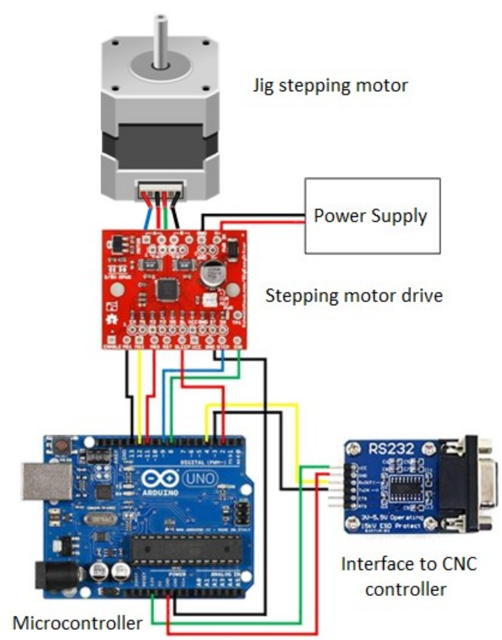


Fig. 3. Polishing jig controller implementation.

Table 1

G-code example for Haas™ machine tool

Point 1	Point 2	Point 3
DPRNT[#101[30]]; G01 X10. F200.; /#101=500;	DPRNT[#101[30]]; G01 X20. F200.; /#101=400;	DPRNT[#101[30]]; G01 X30. F200.; /#101=300;

the polishing tool, and these are sent using the DPRNT command to the microcontroller. As an example, Table 1 presents typical G-code commands for three consecutive points on X axis using feed of 200 mm/min and dropping finishing force respectively proportional to 500, 400 and 300 units.

AccelStepper™ library was included in the 90 line microcontroller program by which trapezoidal velocity profile related kinematic calculations were performed according to the equations of Section 3, see Appendix.

5. POLISHING EXPERIMENTS

The Novapax™ system was adopted for the experiments, involving tools of ring section supported on a 2 DOF mandrel, see Fig. 4.

Diamond coated ring is used for grinding; bronze is used for lapping and plastic for fine lapping. Diamond slurry with different grain sizes is associated with lapping and fine lapping, namely 28, 15, 10, 7 and 3 μm. The optimum process conditions for steel surface finishing are shown in Table 2.

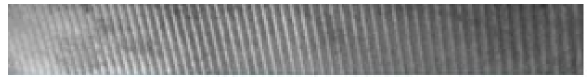
The purpose of the experiments was to test the ability of the device itself to impose a normal polishing force following an arbitrary pattern. Polishing force is required to be constant as long as the contact area between the polishing tool and the polished surface is constant. When the latter changes due to local surface curvature variation the polishing force needs to change accordingly. Therefore, in the general case, a pattern of variation of the polishing force along the polishing trajectory is expected and should be followed by the jig.

Fig. 4. Close-up of polishing jig mounted on cnc mill with rotating mandrel and ring shaped tool.

Table 2

Optimum process conditions [19]

Phase	Ring material	Force (N)	Speed (rpm)	Feed (mm/min)
Grinding	Diamond	7	18000	200
Lapping	Bronze	2	8000	200
Fine lapping	Plastic	7	15000	300



a

b

Fig. 5. Surface state: *a* – initially; *b* – after grinding in the presence of vibrations.

For this reason, finishing was performed on a flat steel specimen using a straight rather than a trochoidal path and the nominal force pattern was compared to the corresponding experimentally obtained pattern.

Figure 5 shows an aspect of the flat specimen used for the experiments. The Kistler 9257A three-component dynamometer was used to measure polishing forces. In particular, the vertical component of the finishing force was focused on.

It has to be noted that during the first grinding experiments using a diamond ring, strong oscillations of the jig were observed, leading to deviations from the linear path. This was diagnosed to be due to flexible coupler eccentricity on the motor shaft and a resulting imbalance.

6. RESULTS AND DISCUSSION

All stages of finishing were performed, i.e. grinding with a diamond ring, lapping with a bronze ring and diamond paste with grains of sizes 28, 15, 10 and 7 μm and finally fine lapping with a plastic ring and diamond paste with grains of size 7 μm.

Two force patterns were tried, namely a random variation and a periodic variation. The first one was deemed more representative of the actual requirements in curved surfaces, e.g. of dies and moulds, dictating a change in force proportional to the curvature variation in order to maintain polishing pressure constant. Periodic variation of force between 3 N and 8 N was tried for fine lapping with a plastic ring, as a special case enabling easier observation of the tendency of the force to keep up with the imposed pattern.

Figure 6 shows the measured force variation with time in comparison to the nominal force pattern that was programmed in G-code and imposed by the microcontroller. The measurements recorded by the Kistler™ dynamometer were processed in the Matlab™ programming environment applying a low pass filter for denoising purposes.

The main force pattern involved changes between approximately 1 N and 5 N, see Fig. 6,*a*–*e*. It is observed that the experimentally measured force does follow the shape of the nominal force curve with deviations in the range 0.5–3 N. Generally, as the grit size decreases it seems that force deviations also decrease, the maximum dropping from 3 N to 1.5 N for paste grit sizes 28 μm to 7 μm respectively.

Periodic force pattern was satisfactorily followed by the measured force yet with deviations in the range 0.7–2.5 N.

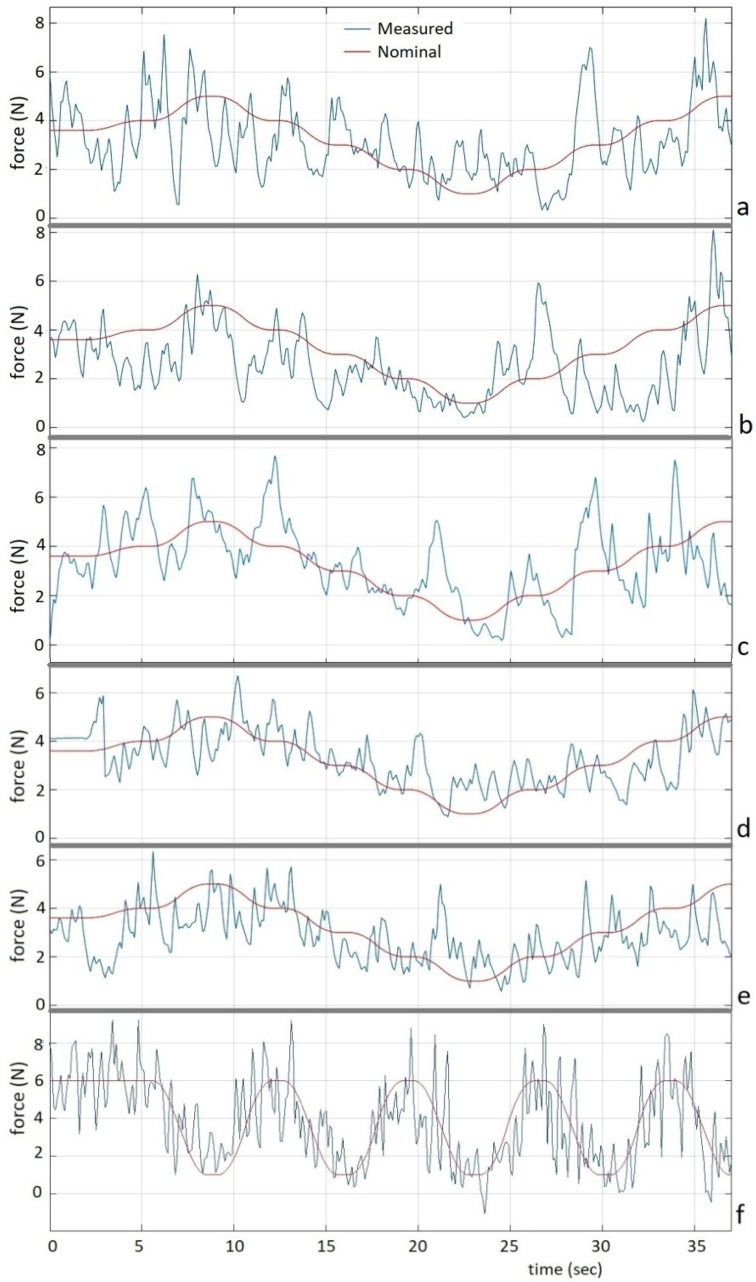


Fig. 6. Measured vs nominal force: *a* – grinding; *b* – lapping – 28 µm grit size; *c* – lapping – 15 µm grit size; *d* – lapping – 10 µm grit size; *e* – lapping – 7 µm grit size; *f* – lapping – 7 µm grit size and plastic ring.

Note that deviations stated above are considered on a local and not on an "envelope" basis, always referring to the corresponding nominal force value applicable for the particular time instant. Note also that measured forces in some cases, see Figs. 6,*c* and *e*, seem to deviate severely from the nominal mean force towards the end of the measurement window, i.e. at $t = 36.5$ sec. However, this is just a matter of presentation cut-off, since the duration of the process was much longer. In fact, similar observations may be made at several other points, see e.g. Fig. 6,*a* at $t = 9$ s, Fig. 6,*b* at $t = 10$ *s*, etc., where the continuation of the measurements clearly show compatibility with the nominal pattern.

In the sinusoidal force case, see Fig. 6,*f*, the nominal pattern is clearly followed quite consistently.

7. CONCLUSIONS

Open loop control paradigm with trapezoidal velocity profile was prototyped using low cost equipment, which was made possible by the mechanical design of the polishing jig. The mean force variation is close enough to the intended nominal one, but strong force value deviations were present. Damping should suppress these deviations and is to be implemented as immediate future work.

Closed loop control will be implemented next, most probably using a DC servo motor, using force or position sensor measurements as feedback. PID or other modern control paradigms resulting from modelling system dynamics are to be implemented and compared.

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APPENDIX: Microcontroller program

```
#include <SoftwareSerial.h>
#include <AccelStepper.h>
#include <stdlib.h>
#include <math.h>
#define enable_stepper1 2
int Vmax = 700;
char var[4];
int i = 0;
int F;
float F1 = 0;
float x1;
float x0 = 15.0;
float xmax=75.0;
float dx;
float dF = 0;
float k = 0.36;
float W = 18;
float F0 = (W - k*x0);
float Fmax=F0 ;
float Fmin= (W - k*xmax);
int StepsPerRev = 200;
int fr = 200; //CNC feed rate mm/min
int dS = 10; //CNC G01 distance mm
float t1 = dS / (fr / 60);
float tf = t1;
float A;
float tb;

SoftwareSerial mySerial(4, 3);
AccelStepper stepper1(AccelStepper::DRIVER,9,8);
void setup() {
  //Stepper Motor Setup
  stepper1.setMaxSpeed(Vmax);
  stepper1.setEnablePin(enable_stepper1);
  stepper1.disableOutputs();
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);
  pinMode(8, OUTPUT);
  digitalWrite(11, LOW); //full step
  digitalWrite(12, LOW);
  digitalWrite(13, LOW);
  digitalWrite(8, LOW);
  stepper1.setPinsInverted( false,false,false);

  //Serials Setup
  mySerial.begin(19200);
  Serial.begin(9600);
}
void loop() {
  i = 0;
  while (mySerial.available() > 0) {
    var[i] = mySerial.read() ;
    Serial.println(var[i]);
    i++;
  }
  F = atoi(var);
  F1 = float(F / 100.0);
  if ((F1<Fmin)||(F1>Fmax)){
    exit(0);
  }
  if (F != 0) {
    dF = (F1 - F0);
    dx = -(dF / k);
    A = Vmax / (tf-fabs(dx/2)*StepsPerRev/Vmax);
    tb = Vmax / A;
    if (tb >= tf / 2) {
      A = 4 * fabs(dx/2)* StepsPerRev /(tf * tf);
    }
    stepper1.setAcceleration(A);
  }
  if (dF != 0) {
    stepper1.enableOutputs();
    stepper1.move((dx / 2)*StepsPerRev);
    while (stepper1.distanceToGo()) {
      stepper1.run();
    }
    if (!stepper1.distanceToGo()) {
      stepper1.disableOutputs();
      F0 = F1;
      F1 = 0;
      dF = 0;
      dx = 0;
    }
  }
  for (i = 0; i < 4; i++) {
    var[i] = '\0';
  }
  F = 0;
}
```