Low-cost, High-Capability, Embedded Systems for CNC Education and Research

Lo Valvo E.[1]
[1] Università degli Studi di Palermo, Dipartimento di Ingegneria Chimica, Gestionale, Informatica e Meccanica, Palermo, ernesto.lovalvo@unipa.it

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Abstract

Teaching of CNC and CAD/CAM technologies has recently taken a great importance, due to their development, to the great number of solutions available on the market, and to the frequent updates. Nevertheless, one of the most urgent need is to improve the quality of education coping with a rapidly growing number of students.
Nowadays, in comparison to the past, many Open-Source technical solutions, both hardware and software, are available to realise easily and cheaply some scaled-down prototypes of numerical control machine tools: these are able to work perfectly and can be employed as a learning method.
This paper shows some past experiences regarding the development of some degree thesis works. In particular, it is shown how to implement a numerical control (LinuxCNC) in two specific cheap embedded systems (Raspberry Pi and BeagleBone Black). In this way, a student has the possibility of simulating the working of a complete Numerical Control and of learning interactively its way of programming.
The final result and student response have shown an excellent effectiveness of these experiences and easy to use as powerful tool in engineering education.

Keywords: CNC, Open Source, Embedded systems

1 INTRODUCTION

Teaching of CNC and CAD/CAM technologies has recently taken a great importance and one of the most urgent need is to improve the quality of education coping with a rapidly growing number of students.
The problem is relevant not only to educational institutions but also to companies that need to instruct their technicians on Numerical Control technologies. Teaching of CNC technologies requires high quantity of practical activity on specialized software and many practical examinations in order to verify correct learning. It is manifest that these activities are more difficult and less efficient when the number of students becomes higher. Therefore there is a clear need for more efficient learning aids for these demonstrations.
Nowadays, in comparison to the past, many Open-Source technical solutions, both hardware and software, are available to realise easily and cheaply some scaled-down prototypes of numerical control machine tools: these are able to work perfectly and can be employed as a learning method [1-2]. Since a factory model simulator can run thousands of times faster than the real factory operations, students would have a rapid, non-disruptive methodology for testing various manufacturing strategies. Improvements suggested by real operations could be tested without risk in the simulation.

However in some cases, either equipment complexity or excessive costs make it impossible for an inexperienced operator to take charge of them. Moreover, workers training is essential and new European educative policies provide for these aspects and highlight the need for a true continuous education [3]. Several studies have shown that changing from such a traditional teaching approach as classroom lectures into an interactive and teaching approach is feasible and has a positive influence on the student motivation [4].
It is hard to overlook the growing presence of electronic and information technology in engineering. However, high-end electronic platforms are often too expensive to be included in education. This obstacle can currently be eliminated by taking advantage of the Open-Source electronic hardware as well as the associated software. Such devices are inexpensive, and they have already made their way to applications in many areas [5-6].
Therefore it has thought to develop some degree thesis works destined to implement a numerical control (LinuxCNC) in two specific cheap embedded systems (Raspberry Pi and BeagleBone Black). In this way, a student has the possibility of simulating the work of a Numerical Control and of learning interactively its way of programming.
Then, it has been possible to construct a scaled-down CNC machine to learn how stepper motors, 3D axis controllers and CNC work at a minimal cost.
Finally, it has been connected a mini milling machine (RM Minimill) for the manufacturing of mechanical components and complex curves like NURBS.

2 ARDUINO PLATFORM

One of the most popular Open-Source electronic platforms is Arduino. According to the official Web site [7]:
"*Arduino can sense the environment by receiving input from a variety of sensors and can affect its surroundings by controlling lights, motors, and other actuators*".
The basic Arduino microcontroller comprises an ATmega chip and contains 14 digital inputs/outputs and 6 analogue inputs. It can be powered from battery, mains adaptor, or computer (via USB port). The scripts (also referred to as “sketches”) can be written in a language derived from C using free integrated development environment (IDE) software, and uploaded to the Arduino board via the USB port. Arduino microcontrollers are currently used by hobbyists and professionals all over the world to automate many different operations. However, the platform has already found applications in many fields including the manufacturing processes with numerical control [8, 9].
Then, after some analysis about different solutions, it has thought to start by modifying a small a manual hobbyist milling machine (Proxxon BFW 40/E) to implement a low-cost numerical control based on Arduino. This has been carried on employing some stepper motors coming from some old printers and a shield low-cost for Arduino (CNC Shield V3.00 [8]) which uses an Open-Source software (GRBL 0.9g [9]) for machine control (fig.1).
This work has been performed as thesis work and has allowed the students to experience many activities which weren’t developed during academic courses. Notwithstanding the success of this experience, yet this solution has not been demonstrated suitable enough for its employing in large scale for some hardware and software inadequacy. In particular, as

well as the requirement of a classic computer, hardware and software modest features enable to test only some simple numerical control manufacturing processes.

Figure 1. Modified small hobbyist milling machine

3 ARM PLATFORM, RASPBERRY PI AND BEAGLEBONE BLACK

On basis of this experience, it has thought to employ some similar more powerful devices, able to use also inexpensive hardware but more suitable for educational utilization [10-11].
The attention has been drawn to a project called Machinekit [12] whose aim is to use an Open-Source software for CNC machines (LinuxCNC [13]), much more well-versed of GRBL, on low-cost devices based on ARM processor. In particular it has been implemented the numerical control LinuxCNC in two specific cheap embedded systems (Raspberry Pi and BeagleBone Black) [14, 15].

Figure 2. Raspberry Pi and BeagleBone Black

3.1 Raspberry Pi

The Raspberry Pi project has been announced at the end of 2011 as the smallest computer in the world [14]. A very low cost computer has been implemented on a single board whose

dimensions are similar to a credit card. The project born to support teaching of computer science and programming at school.
The core of system is a multimedial processor BCM2835 type SoC (System on Chip), formed by following components:

- Processor ARM1176JZ-F 700 MHz
- Coprocessor Dual Core VideoCore IV Multimedia
- Video Card Encode/Decode 1080p30 Full HD H.264
- VideoCore GPU Low power, OpenGL-ES 1.1/2.0, 1 Gigapixel per second
- Simultaneous video output for LCD and HDMI with HDCP at 1080p60

Given that almost all main components of a computer are present, i.e. the processor (CPU), the graphic elaboration unit (GPU) and communication hardware, and being able to run an operating system as Linux, it has been employed in many different kinds of applications (server, domotic, media center, etc.).
To implement the numerical control software, it has been followed the method presented by some users [16].

3.2 BeagleBone Black

BeagleBone Black is a low-cost, community-supported development platform for developers and hobbyists [15]. The system has the following main features:

- Processor: AM335x 1GHz ARM® Cortex-A8
- 512MB DDR3 RAM
- 4GB 8-bit eMMC on-board flash storage
- 3D graphics accelerator
- NEON floating-point accelerator
- 2x PRU 32-bit microcontrollers
- HDMI
- 2 x 46 pin headers

Even in this case the hardware enable to use the Linux operating system which makes the employing possible in many fields [17].
To implement the numerical control software, it has been followed the procedure reported in this blog [18].

4 CONSTRUCTION OF A SCALED DOWN MINI CNC MACHINE

After having checked the functionality of LinuxCNC, the two systems are already able to simulate a standard Numerical Control, enabling the students to verify the ISO language programming and learning interactively through video simulation CNC codes.
The next step has been to proceed to a real motion of a machine.
Therefore it has been thought to build a small machine prototype using as motion system the mechanism of 3 old floppy disk, by now disused, but able to realize movements similar to those ones of a classic three axes CNC machine, using the same ISO language. In fact the floppy drive electronics enables the motion command along an axes linking fittingly and

directly floppies at GPIO ports present on the two boards. In fig. 3 and in video (http://youtu.be/lH1DRe-STvs) [19] is shown the first steps of functionality test.

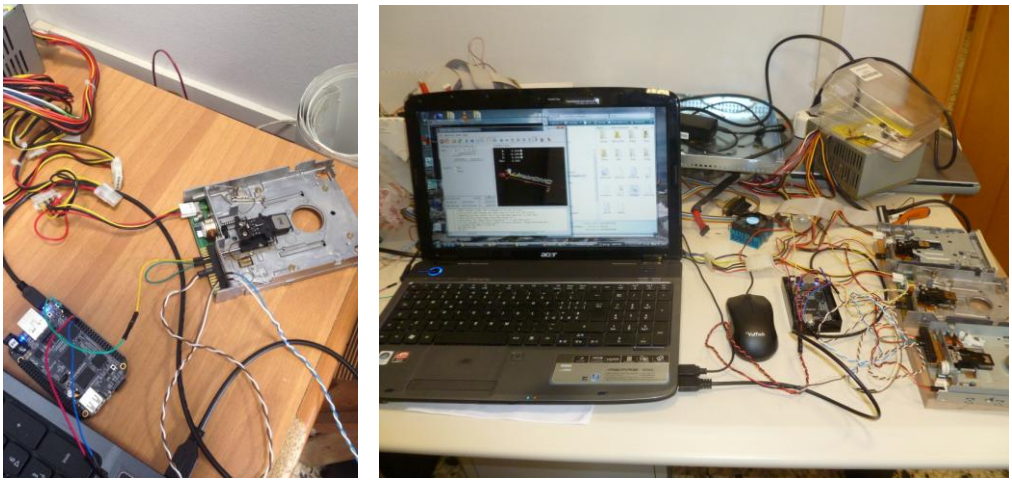

Figure 3. Floppy drive connection

Checked the feasibility of the solutions, it has been proceeded to build a three axes machine mini prototype whose motions have been controlled by LinuxCNC software (fig.4). The overall expense for this machine, even including ARM board, is largely lower than 100 euro. The tool has been simulated using a marker which draws by standard ISO codes. The results of this work are also visible on YouTube (http://youtu.be/xq1JUozQB60) [19].

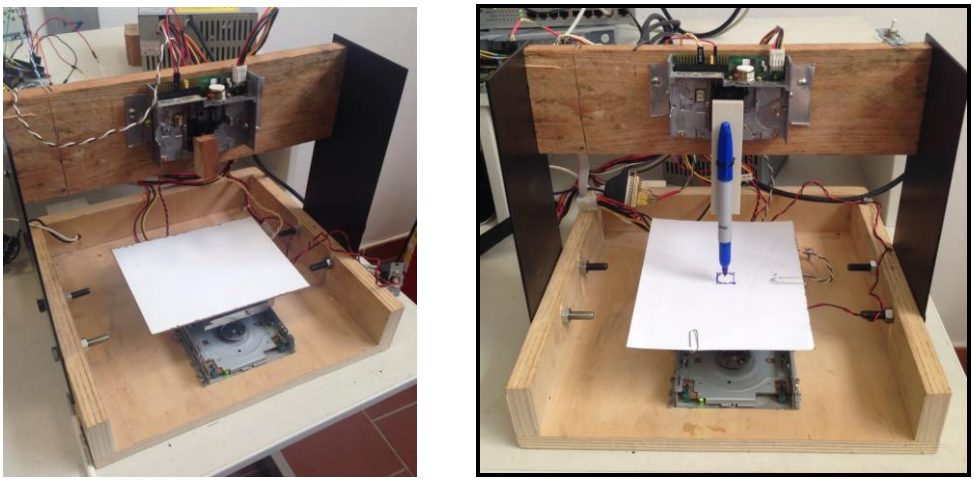

Figure 4. Scaled down mini CNC machine

5 INTERFACING ARM BOARD WITH CNC MINI MILLING MACHINE

The further step has been that one to use both the modified hobbyist milling machine, previously employed with the Arduino board, and a mini milling one already present in the laboratory (RM Minimill).

3.1 Raspberry Pi

In the case of Raspberry Pi, more popular board, however the shortage of output GPIO has required the utilization of an additional board which has also made utilization of CNC shield, previously employed with Arduino board, possible. Raspberry Pi is equipped with a GPIO port, unfortunately formed by few pins, a condition which restrict the connections with many devices simultaneously. Furthermore this makes worse all performance of the board.
To overcome this problem some users have suggest to connect Raspberry Pi, by SPI link, with a FRDM-KL25Z board and to insert Arduino CNC Shield above it [16].
The FRDM-KL25Z is a low-cost electronic card (about 10 €) based on new type of MCU ARM belonging to Kinetics family made by Freescale with form-factor compatible with the Arduino pin layout, providing a broad range of expansion board options as CNC shield.
The FRDM-KL25Z is the first hardware platform to feature the Freescale Open standard embedded serial and debug adapter known as OpenSDA. This circuit offers several options for serial communications, flash programming and run-control debugging. The on-board interfaces include an RGB LED, a 3-axis digital accelerometer and a capacitive touch slider.
In fig. 5 some photos of the connection are shown.

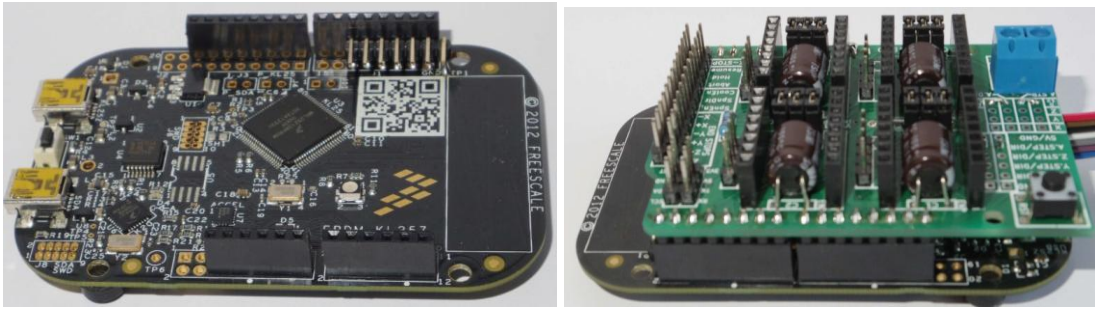

Figure 5. FRDM-KL25Z and CNC Shield

Even if the goal has been achieved, however performed experience has shown some difficulties due to a unsuitableness of the Raspberry Pi hardware that, though it pilots the machine, is inadequate to use AXIS graphic interface, widely used in LinuxCNC.

5.2 BeagleBone Black

For Beaglebone Black instead it has been preferred to use a shield compatible even with the RM Minimill present in the laboratory. Among the available boards, the choice has been fallen on bbb_parport [20], directly utilizable with RM Minimill with a parallel port emulation.
In fig. 6 some photos of BeagleBone Black and bbb_parport and are shown.

Figure 6. BeagleBone Black with bbb_parport

In this case, the work has been resulted more simple and only concerned the customization of configuration of RM Minimill. An example of machining is visible in fig. 7 and in video (http://youtu.be/xxfehWydTzk) [19].

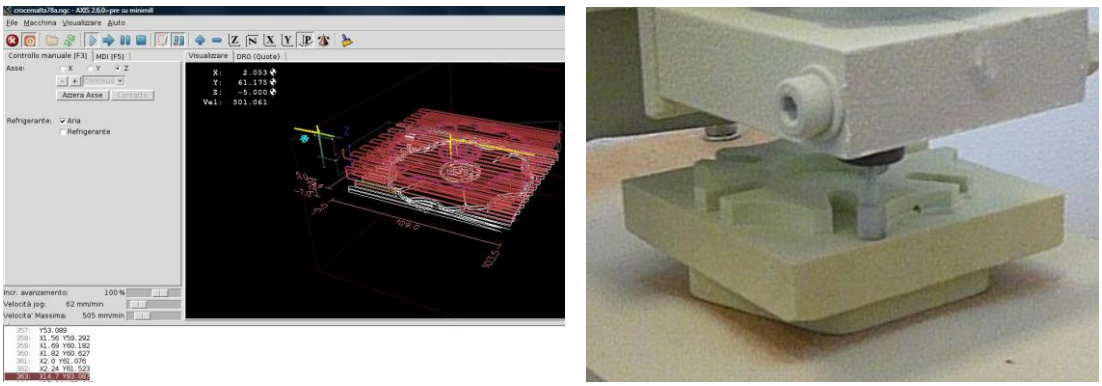

Figure 7. An example of machining with CNC machine

In comparison with the Raspberry Pi, the BeagleBone Black performances have been demonstrated so superior that it has been also possible to perform complex profiles as NURBS directly (fig. 8 and http://youtu.be/BFiAHCX2VVk [19]), utilizing a proper modified LinuxCNC version [21, 22].

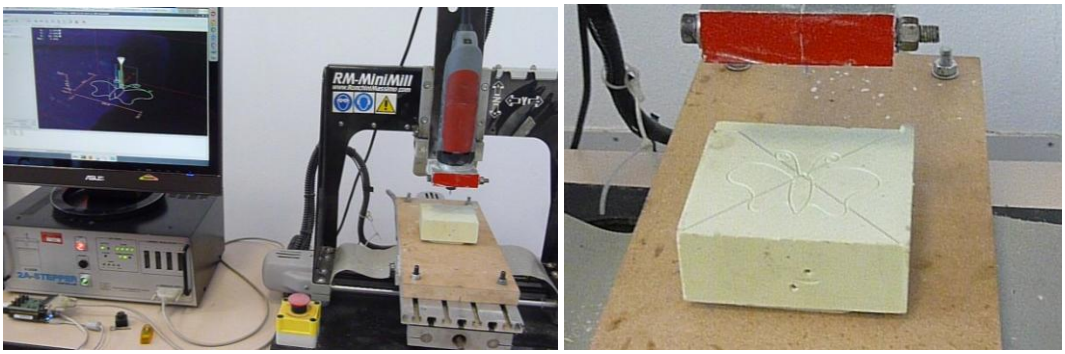

Figure 8. NURBS machining with BeagleBone Black

6. CONCLUSIONS

In this work an integration of a Open-Source Numerical Control on two low-cost embedded systems is presented. It allows users to perform a preliminary check of both the part program and the tool path; it also allows not only to predict NC machine behaviors before using it, but also to drive the machine.
A comparison between two different approaches has been performed.
It can be noticed that is an great opportunity for students and researchers to investigate the whole structure of the software and thus to understand the principles on which a modern numerical control system is based; moreover, it allows users to freely modify the structure.
LinuxCNC has been successfully used as a numerical control system for a milling machine, proving great flexibility and adaptability thanks to its peculiar architecture.
The LinuxCNC features, such as the presented ones, have been developed using HAL, a powerful tool which allows users to integrate any special hardware with the software; as a matter of fact, it is able to control the machine-tool and to simultaneously show a model, displaying the same behaviors of the real machine. Also, since the source code is free and available on the Internet, it is possible for anyone to make further changes to the software has been possible allows LinuxCNC its ability to machine the so-called "complex curves", such as the B-Spline or NURBS.
Another important thing is that the students involved have shown much interest in this activities, because they have had the opportunity to put into practice directly, easily and inexpensively the topics learnt during academic courses, which is a great help for designers and users in training (i.e. both users involved in the management of CNC controls and students from schools and universities).
It has been particularly appreciated the possibility of testing even new areas of applications. In fact, following the studies of some researchers, it has been working to add a head extrusion to mini milling machine in order to realize a mini 3D FDM printer. This allow users to experiment additive and subtractive manufacturing in one system.

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