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Development of Desktop Multipurpose Grinding Machine for Educational Purposes

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Abstract

Given the growing popularity of the maker movement, it is proposed that affordable machine tools may be desirable for both teaching purposes in universities and high schools and use at home by Do It Yourself enthusiasts. For the concept to become a reality, it is necessary that the machine tool can be easily assembled and disassembled by an end-user (e.g. student or hobbyist) and can adapt to changing projects or machining requirements. In this paper the concept and initial development of such a desktop multipurpose machine tool is reported. Through the use of modular robot modules, it is demonstrated that a machine can be converted from an outer diameter grinding to freeform grinding configuration in approximately 15 minutes. The initial prototype machine will be used to demonstrate concepts such as miniaturization, multi-functionality, and re-configurability for machine tools to undergraduate and high school students.

Keywords: Desktop Machine Tools, Grinding, Education

1 Introduction

In recent years there has been a growing trend towards downsizing of machine tools used for the production of small parts due to the economic, social, and environmental benefits, including reductions in space requirements, capital investment, running costs, energy and material usage, noise and vibrations (Okazaki et al., 2005). The development of desktop milling, turning, and grinding machines have been widely reported in the literature (Okazaki et al., 2005, Subrahmanian and Ehmann, 2002, Walk and Aurich, 2014). An interesting further development of the desktop machine concept is the addition of multi-functionality to the machine tool. For example, the desktop machine developed in (Kurita and Hattori, 2005) for the production of molds, allowed for milling, electro-discharge machining, and electrochemical machining. An additional social benefit of multi-purpose machine tools is their suitability for small industry and remanufacturing in developing countries e.g. (Aguilar et al., 2013) developed a combined lathe and mill for the local jewelry industry in Mexico. In contrast to reconfigurable machines tools, which are designed around a specific part family with limited flexibility (Katz, 2007, Padayachee and Bright, 2012, Koren et al., 1999), such machine tools increase

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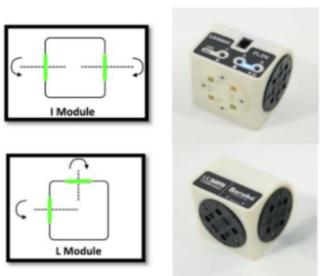
the flexibility of existing CNC machines with additional machining capabilities. The application of desktop and multipurpose machine tools therefore forms an important role in the development of sustainable manufacturing (Liow, 2009).

In order to include this topic in a manufacturing engineering educational curriculum, a senior undergraduate student engineering team was tasked to design and develop a desktop and multipurpose machine for outer diameter and surface and/or freeform grinding. The main objectives of the project were to: 1. Demonstrate and engage undergraduate students on the topic of desktop and multipurpose machine tools and 2. To develop knowledge of machine tool development within our laboratory, with a view to further exploring such machine tools for hobby/Do It Yourself (DIY) users. The challenge for the students was to develop the grinding machine with a limited budget, and therefore it was necessary to utilize existing departmental resources as much as possible. The maximum budget was $1,000. An added motivation and interest for the students was the development of cost effective machine tools for DIY/Hobby users, given the growing popularity of the maker movement. A potential application for the desktop grinding machine includes the finishing of round parts and engraving of workpieces such as toys, personalized plates etc. The developed multi-purpose grinding machine will form the basis for future laboratories and class discussions. The envisaged target audience is undergraduate and high school students.

2. Student Project: Team and Resources

A group of three senior year undergraduate students were commissioned to develop the desktop grinder, as part of a two-quarter design project. In order to design the various elements of the machine tool, the students used theories and experiences from their engineering curriculum including statics and dynamics modeling, stress and failure analysis, design for manufacturing, and numerical methods. In addition, stress analysis and programming were performed using Solidworks, MATLAB and Ch (programming language for the motor elements) respectively. Given a very limited budget, the students were instructed/constrained to utilize existing resources as much as possible. Therefore nearly all of the parts, including critical machine components such as robot arm, tool holder, base, and feed drive, were fabricated by the students in the department's machine shop using lathe, mill, and bending brake. A Dremel 4000 power tool was provided as spindle and allows for use of a wide variety of tool bits and cutters including grinding wheel, drills, sanding disc etc. Linkbots (figure 1) by Barobo Inc. were provided for rotary motion. The Linkbots are modular robots with two rotational joint, built in 3-axis accelerometer and absolute position encoder, and on board rechargeable battery. The mechanical interface on the Linkbot surface created a standardized mechanical interface for all custom components and the integrated control system (BaroboLink) greatly simplifies the simultaneous communication between multiple modules.



- Maximum torque per motor is $0.7\ Nm$
- Maximum rotational speed is $40\ rpm$
- Internal 9V Li-Ion battery
- Runs on Python and Ch
- Bluetooth Zigbee connection

Figure 1: Linkbot I and L modules and specifications

3. Desktop and Multipurpose Machine Tool Concept

A number of conceptual designs were proposed by the students, and the final selected design for a multi-task grinding machine is shown in figure 2. The first configuration provides for outer diameter cylindrical grinding, and requires four motor modules and three degrees of freedom. The second configuration allows for contour and complex geometry machining e.g. sculpturing. It uses the same four motor modules in the previous configuration but with five degrees of freedom for increased flexibility. The novelty of the machine tool concept is the ability to re-configure the machine setup within a short time frame. The use of modular components allows for ease of assembly and disassembly in the same manner as Ikea furniture, and in a similar manner the components are assembled using standard tools such as screwdrivers, wrenches and hex keys. The team also developed a user manual with detailed assembly instructions which includes step-by-step picture based instructions, and a list of required tools. Combined with open source programming, a customized machine tool can be developed based on user driven product/workpiece ideas. Therefore in contrast to traditional machine tool design, which are typically based on predefined workpiece dimensions and required tolerances, the proposed approach prioritizes total flexibility. Therefore while figure 2 demonstrates two possible machine configurations, it is envisaged that many more could be developed by end-users.

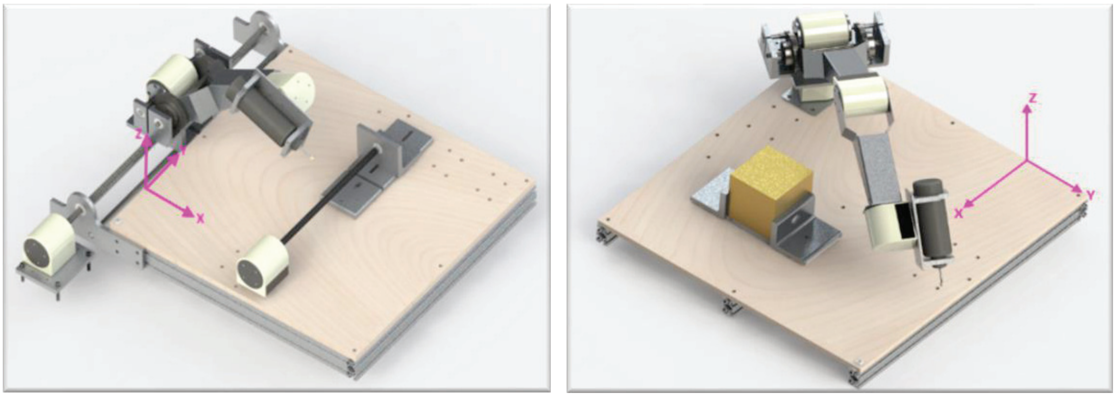


Figure 2: Desktop machine tool for outer diameter (left) and freeform grinding (right)

4. Machine Design and Analysis

As no specific product/workpieces were defined, the students were not required to calculate torques and cutting speeds but instead to focus on conceptual design with a view to producing a ”model machine tool”. Solidworks software was used for the 3D design and modelling of the different parts. The base provides the foundation for all other subsystems including the feed axis, workpiece, and robot arm. It is designed to be robust and provide a steady working surface which is resistant to vibrations arising from grinding forces. In addition, the base is fitted with multiple attachment points to provide flexibility when placing the workpiece. The majority of the base is made of attachable aluminum T-slotted framing, which allows flexibility in part placement.

Some of the major machine components including arm module, linear feed drive assembly and tool holder are shown in figure 3. The arm/link plate was made out of sheet metal in order to reduce component weight while maintaining strength. For complex geometry grinding configuration, the

Linkbot furthest from the grinding tip is crucial since it supports the weight of three Linkbots, the metal linkage plate, the tool holder, and the tool. However, the motor of the Linkbot is a limiting factor since each module can support a maximum torque of 1.4 Nm (0.7 Nm for each motor). Due to the insufficient torque output of each motor, a large external gearbox was required and developed to hold the arm under its own weight. For the outer diameter grinding operation, an additional linear feed drive is necessary to convert rotary motion into linear motion. The linear feed drive moves the platform/carriage supporting the robotic arm (figure 3). A basic finite element based stress analysis (figure 4) was conducted for the arm module in order to ensure an adequate safety factor under eccentric loading. The critical stress points are in the green zones (approx. 21 MPa), and are well below the yield strength of aluminum.

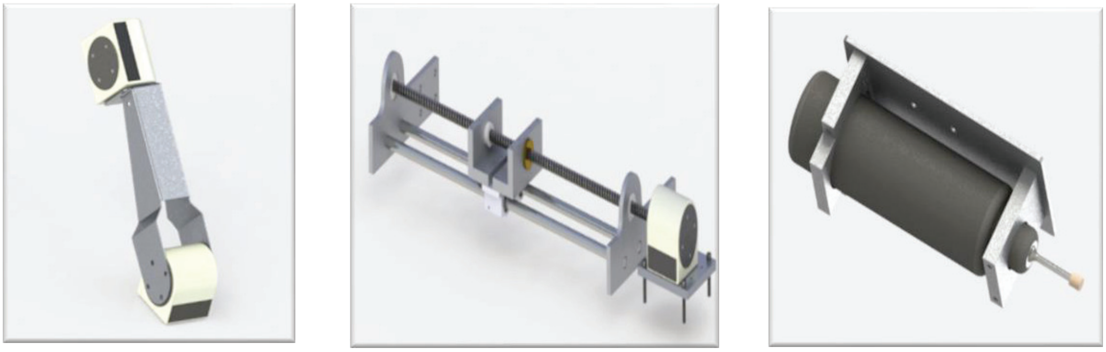


Figure 3: Arm module, Linear feed drive assembly and Tool-holder

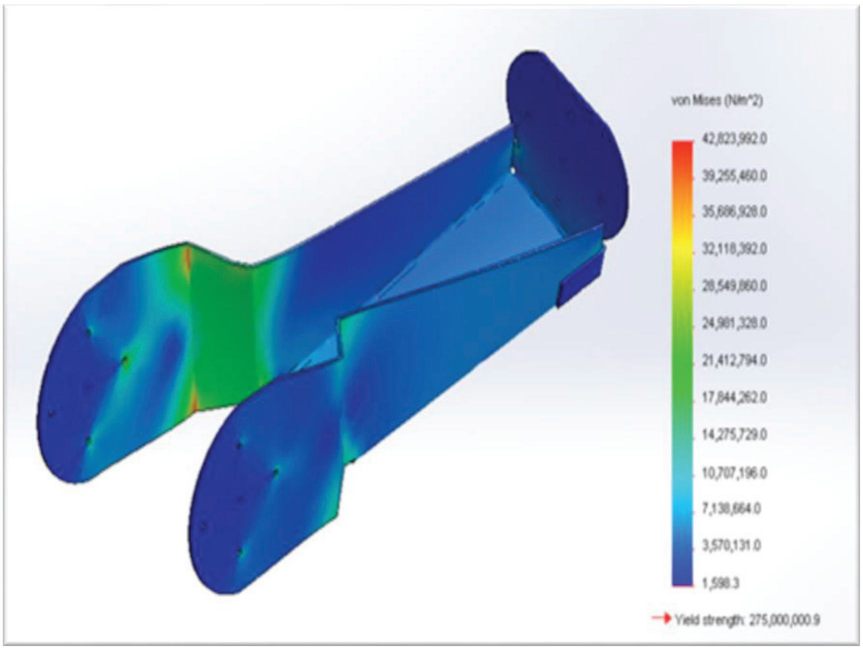


Figure 4: Arm module stress analysis

The Tool-Holder secures the Dremel spindle/tool and absorbs any shocks encountered while grinding (figure 3). The Tool-Holder was designed to be: 1. Lightweight in order to reduce the amount of inertia on the Linkbot motors. 2. Capable of absorbing moderate amount of shocks and vibrations. 3. Sturdy enough to not bend under the grinding forces. Aluminum was selected for the tool-holder material for its high strength to weight ratio. Two adjustable aluminum blocks were used to secure the Dremel on the Tool-Holder base and a custom rubber grommet was inserted on the rear end of the Dremel to absorb any vibration to the base. The spring and damper properties of the rubber grommet were judged (by the students) sufficient to dampen a majority of the incoming vibrations.

The software required to program the desktop machine tool included: ChIDE Student Edition, BaroboLink, Linkbot Firmware and MATLAB. The methodology for configuring and running the grinder is shown in figure 5. A pose teaching feature allows the user to physically place the arm and then record the angular positions of each Linkbot. This helps bypass the need for complex reverse kinematics algorithms. With the outer diameter machine configuration, it is possible to control movements in the Y direction independently from the movements in the X-Z plane, further reducing the control complexity. Reduction in complexity translates to the ease at which the inputs can be solved when a desired output is given. Instead of solving three variables—the joint angles on the Linkbots that set the tooltip to the desired X, Y, and Z coordinates —simultaneously, the joint angles that yield X and Z positions can be solved by closed form inverse kinematic equations while the joint angle responsible for the Y positions can be solved independently. The linear drive, which allows the tool to move in the Y direction separately, is conceived from the result of this simplification. In contrast, the freeform grinding configuration, in its current state, is restricted to pose teaching programing because all of the Linkbot joint angles must be solved simultaneously. In addition, the lack of an analytical solution calls for iterative approach, which requires additional programming and increases calculation time to find the desired inputs for the respective Linkbot joint angles.

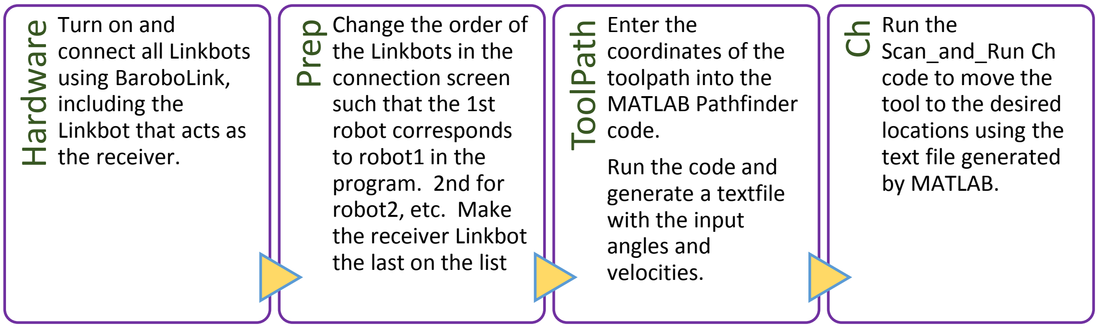


Figure 5: Method for configuring and running the grinder

5. Initial Prototype and Discussion

The developed multi-task desktop grinding machine is shown in figure 6 in outer diameter and freeform grinding configurations. The machine setup can be changed in approximately 15 minutes. A limited number of initial tests indicate the tool can follow a desired path, though the accuracy and repeatability has yet to be assessed in detail. Clearly however, factors such as undersized motors, low cost sensors and (deformable) plastic housing will result in a low positioning accuracy in comparison to industrial type machine tools. To assess the current performance, and understand future challenges for the customizable machine tool described, extensive experimental testing will be conducted to quantify stiffness of the kinematic chain, flatness and straightness of XYZ stages, spindle runout etc. In addition, alternative modular motor modules and machine structures will be investigated to reduce control complexity and improve rigidity along with accuracy. For 3 to 15mm diameter tooling, a positioning accuracy of 0.1mm is deemed sufficient and will be a target for future work. For comparison, the theoretical tolerances and positioning precision achievable with current desktop 3D printers is generally around 100 μm (0.1mm) also.

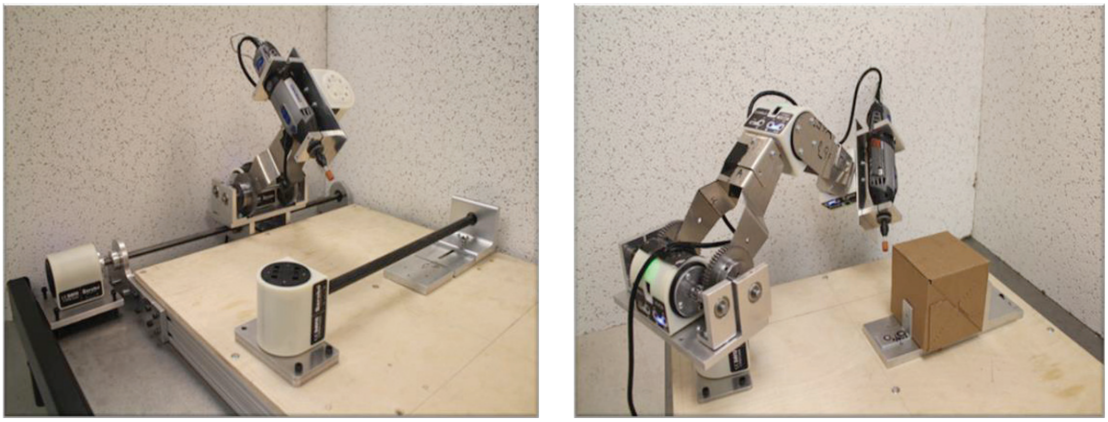


Figure 6: Outer diameter and freeform grinding configuration

6. Conclusion

The paper introduces the concept of a multi-purpose desktop grinding machine tool and its early stage developments. In its current state, the machine is not suitable for machining purposes but serves as a useful introductory demonstration for students, to highlight the important elements of a machine tool in general, and the challenges in machine development. This initial prototype will serve as a starting point for further investigations and development of the concept. Another student project will determine the achievable accuracy in machining in its current form, and investigate the required modifications to make the machine suitable for end-users in the future. In particular, the rigidity of the arm module and other structural components, a crucial performance indicator during cutting, will be assessed with a view to future improvements. Outer diameter cylindrical grinding machines, for example, are generally designed for high stiffness, and therefore the trade-off between flexibility and rigidity requires further investigation. Future design will also incorporate some of the structured methodologies that have been developed for machine tools in general (Altintas, 2012, Dornfeld and Lee, 2008). From an educational point of view, it is hoped that students will ultimately be able to assemble and program the machine tool in order to learn about machine tool components and the challenges facing machine tool developers.

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