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Real NC Control Unit and Virtual Machine to Improve Operator Training

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Abstract

This paper describes a coupling between a real NC control unit and a virtual machine and its application potentials for vocational training. First the Hardware-in-the-Loop coupling, including the setup of the machine model, the connection itself and the realized material removal process, is described. Based on that, possible application scenarios for vocational training are discussed. In addition expert opinions about the usability of the NC-VR setup and possible obstacles are presented.

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1. Introduction

Currently, to learn how to operate a machine tool – either because it is a new technology or machine or because someone is undergoing vocational training – is a mix of theoretical lessons and hands-on training at the real machine. For the hands-on training a real machine with the right setup has to be available. And even if that is realizable, it is not (or only with great effort) possible to show every detail of the process or of the machine and to let every student practice as long as he or she needs.

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That is where the virtual reality (VR) technology steps in. With this technology it is possible to visualize realistic, 3D (stereoscopic) scale one to one models, e.g. of different types of machine tools. In addition to the static geometry, it is possible to visualize the whole manufacturing process, to take the machine or components apart, to insert cutting planes or just to walk around the machine and zoom inside. This provides a very good insight into the machine and helps the trainer/teacher to better explain the different functionalities. Furthermore the VR machine model, compared to a real machine, allows quick and easy changes of the setup and the components of the machine, if for example a new manufacturing technology was developed. (cf. [1]) Those are great advantages; but do they compensate the extra effort (money and time wise) for creating the VR model and is it sufficient just to use a digital model for training purposes?

We think the advantages of the VR technology and of hands-on training on real components should be combined. Therefore we propose to use a combination of a real NC control unit and a virtual machine model (NC-VR coupling) for the main part of the training. This paper will describe how such a coupling works and how it can be used for training of machine operators and NC programmers.

In terms of operator training, the coupling between a real NC control unit and VR machine model has a lot of advantages. First of all, the training process can be started when the machine is not yet delivered or commissioned. Second, for regular revision trainings, the real machine does not have to be taken out of the production process. Nevertheless, the training can use a scale one to one representation of the machine controlled by the real control unit.

For training of NC programmers, the NC-VR coupling can be used to test handwritten NC programs – always before they are run on the real machine and especially for education purposes when trainees have to learn how to write such a program. In addition to test handwritten NC programs, the trainees can also see the results of their inputs on a real NC control unit (in terms of the resulting work piece geometry or possible crashes) at a scale one to one model of the machine tool. This testing can be done without risking a machine crash and without using the capacity of a machine in production.

2. Coupling between a Real NC Control Unit and a Virtual Machine

2.1. State of the Art

Nowadays, complex machining programs are automatically generated using ‘Computer Aided Manufacturing’ (CAM) programs. These programs are created in a standardized DIN 66215 and ISO 4343:2000, control unit-independent CLDATA format. Converted via a post-processor to a NC program that can be read by the NC control unit, they are referred to as the G-Code. The G-Code is standardized in accordance with DIN 66025 and ISO 6983. Despite these standards, the control unit manufacturers apply their own data formats, deviating slightly. Therefore a NC program which has been converted to a manufacturer specific NC program (G-Code) cannot be run on the NC control unit from a different manufacturer or on a NC control unit of the same manufacturer that has been configured differently, e.g. other axis configuration for another machine tool. One way to solve this problem is the integration of the real NC control unit within the simulation environment. The coupling between a real control unit with a simulation environment is called Hardware-in-the-Loop (HiL) simulation.

The automatically generated NC programs usually have great optimization potential such as shorter travelling paths for the individual axes, reduced downtimes or optimized milling strategies. In addition to that, the NC programs sometimes contain errors that only occur during the program run on the real NC control unit. For example, if tools which were previously defined in the NC program do not match the real tools projected in the control unit, machine stop or more dangerous collisions may result. For example the tools could collide with a fixture component that was not considered during NC programming, which could cause considerable damage of the machine. It is necessary to correct these errors and to optimize the automatically generated NC
programs. This optimization will take a considerable amount of time and could also produce many defective tools, if doing this at the real machine tool. Therefore the simulation of the NC program including a virtual model of the machine tool model can be used to identify and correct these errors prior to real production.

Most of the programs which are used to simulate automatically generated NC programs are desktop-based and consist of two software parts – the machine and the NC control unit. Within these Software-in-the-Loop (SiL) simulation systems, the workspace of the machine tool, including aspects such as speed, range of movement of the tool and the accuracy of the work pieces geometry, is reproduced. However, it is difficult to reproduce the whole NC control unit using a desktop-based SiL simulation because NC control units work internally at real-time and are really complex. Therefore these simulations only consider certain aspects of the whole NC control unit (cf. [2]). Nevertheless, different researchers introduced a virtual reality simulation for numerical controlled milling machines using only desktop-based simulation (cf. [3], [4]).

In contrast to a desktop-based simulation, the HiL coupling, which has been developed in recent years, combines a real NC unit with a virtual model of the machine tool. As the NC control units work in real time and the response of the simulation model must take place after a specific time interval, the coupling of the NC control unit with the virtual machine model is the largest challenge. (cf. [5])

For HiL simulations, the depth of the simulation model is most important, because of the real-time constraints. The connection of the NC control unit to the VR machine model is relatively simple if the distances travelled by the machine are optimized and checked for collisions. However, if the individual drives of the machine, especially their masses and inertias have to be reproduced, HiL modeling can be very time-consuming as most drive models use complex, abstract simulation models created, for example, by using Matlab Simulink. These models are used to check and reproduce the individual parameters of the drives. Nonetheless, collision detection of the machine axes can be rather difficult because of their high degree of abstraction. Due to the fact that there are enormous requirements regarding this coupling of the NC control unit, the NC control unit is generally only operated in the so-called simulation mode. In this case, the outgoing target values are returned directly to the internal position regulator as actual values. Using HiL coupling, the NC control unit runs the NC program as usual and the connected VR machine model moves exactly according to the specification. Therefore this coupling variant allows an early inspection of the NC program as well as the identification of possible collisions of the machine axes.

Nowadays, operators of machine tools are usually trained by a combination of classroom education and hands-on training at the real machine tool. For the second part of the training, the machine tool has to be available and out of production. In addition, if untrained operators start to operate the NC control unit, there is a high risk for errors that might even cause injuries or damage the machine. Though, a training session only based on ‘classroom methods’ such as power point presentations is not sufficient because the visualization of the machine tools is not realistic enough for the trainees to learn how to operate a machine, and the interaction with the real NC control unit is missing as well.

The virtual reality technology was basically developed as a visualization tool. At first it was mostly used for presentation and marketing purposes within the automotive and aerospace industry. In recent years the VR technology has been more and more used in different areas of production technology. Nowadays, the overall goal has to be to integrate the VR technology within every section of the product lifecycle. Therefore one step is to use the advantages of the VR simulation for the NC simulation as well as for operator training.

2.2. Hardware-in-the-Loop Coupling

To connect a real NC control unit with a virtual machine model, at least the actual axis values and the current tool from the NC control unit needs to be read and sent to the virtual model without any noticeable delay. There are two possible ways to do that. The first way is the use of a manufacturer-specific automation bus. The second way is to read the relevant values (axis values, tool number, etc.) at the Human Machine
Interface (HMI) from the NC control unit and to send these values via network (e.g. TCP/IP protocol) to the virtual machine model. Both couplings have their advantages and disadvantages. It is very complicated and takes much effort to establish the first variant over the automation bus. The reason for this is that nearly the whole hardware configuration of the NC control unit needs to be changed to send the actual axis values over the automation bus. A firmware update of the NC control unit is also necessary. These changes need to be undone after the simulation in order to use the NC control unit for the real machine again. The second coupling, the direct readout from the HMI, is a good choice when it is not necessary that the drives are part of the simulation system. To implement this type of connection, the NC control unit has to be switched into the so-called simulation mode. In this simulation mode, the control unit does not send rotational speed values to the drives and does not wait for the position values of the measuring system. The closed loop control of the control unit uses the set values as input for the actual position values, i.e. there is no drive simulation necessary. This is the main reason why this coupling is a lot easier to establish. In this variant, the direct readout of the current axis values via the local network is possible, as the NC control unit sends all updated position values to the HMI. For the Siemens SINUMERIK 840Di this internal data transfer takes place via the Windows service Dynamic Data Exchange (DDE). Using this service, the actual axis values, tool number and other necessary values, can be read and sent to any other computer in the local network. The specifically developed program that reads these values is shown in Fig. 1. In the background the regular HMI is shown and in the foreground the developed program SINUMERIK Axis Interface (SAxI) is presented. Here the SAxI sends 5 axis values and the tool number to the computer with the local IP address 134.109.8.156.

![Fig. 1. SINUMERIK axis interface at the HMI.](image)

For the VR machine tool simulation presented here, the actual axis values and the tool number are the relevant values for simulation. These values have to be read from the HMI first and then sent to the simulation environment. After this, the values must be transmitted to the prepared machine model. The preparation of the VR machine tool model is the next important step.
2.3. Preparing the virtual machine model

Usually the original data of the virtual machine are the CAD data. The standard VR data format is Virtual Reality Modeling Language (VRML). VRML is an exchange format and the export is supported by almost all CAD programs (cf. [6], P. 247). Most of the VR programs support a direct import of VRML files. The VRML data structure consists of a 3D scene graph. This scene graph is ideal to reproduce the structure of the machine tool on the basis of its VRML data (cf. [7], P. 84-86).

After the export of the VRML model from CAD, the VRML model is completely static, i.e. without kinematic and animation information. The kinematic structure must then be reproduced directly in the VRML scene graph with the aid of so-called transform nodes. Transform nodes are group nodes, defined in the VRML standard [8]. Each transform node has a coordinate system of its own, groups several objects and allows translational and rotational movements. A separate model preparation, such as polygon reduction can be done to accomplish a higher frame rate of the whole scene (cf. [9]).

The VR machine tool has to be divided at least into the moving axis and the static part of the machine tool, like e.g. the machine bed or housing. The moving parts are the rotary and linear axes. The hierarchy of the VR machine tool must be structured analog to the real machine tool. This can be done using the transform nodes with a unique name for each transform node. Transformation specifications can then be transmitted to the real NC control unit via these nodes. Fig. 2 shows an example of a 3 axis milling machine, realized using the transform nodes in VRML. It is a Deckel-Maho DMP 45 V linear 3-axes milling machine.

![Fig. 2. Hierarchy of the model of the DMP45 V linear 3-axis milling machine.](image)

2.4. Material Removal

Usually material removal simulations calculate the volume that describes the tool during milling process through the workpiece and subtract this volume from the virtual workpiece. But this technique is only possible when using volume based models, e.g. CAD models. However, VRML models are surface based models and therefore this methods does not work. A possible way to calculate the material removal for this 3-axis milling machine is using the VRML elevation grid. When the tool penetrates now the workpiece (represented by an elevation grid) only the points from the grid becomes new elevation values. The great advantage of this method is that the numbers of points, and therefore the numbers of polygons, stay the same during the whole simulation. That makes it a perfect method especially for real-time simulations as real-time VR simulations are dependent from the amount of polygons in the VR scene. The disadvantage of the elevation is the limited
resolution and the limitation that not all machining operations can be simulated with this method, e.g. undercuts are not possible because one point of the grid can only of one high value. Fig. 3 shows the material removal based on elevation grid in the VRML model of the 3-axis milling machine.

![Fig. 3. Virtual milling simulation at the 3-axis milling machine](image)

However, sometimes the machine programmer needs to know the exact outcome of the NC program, and the elevation grid method is not as accurate as needed for a quantitative comparison between the target geometry and the simulated geometry of the work piece. Therefore an offline simulation of the work piece was developed, using a CAD core for the simulation of the material removal. This simulation uses the recorded axis values from the real NC control unit for the machining simulation. The simulated work piece as it is also a CAD data format and volume based could be loaded into a CAD system and compared with the target geometry of the work piece [10].

3. Using NC-VR Setup for Training

In the following Chapter different possible application scenarios for using the NC-VR setup in the context of vocational training are described. In addition we will present some results of an expert workshop where we asked vocational training teachers about their opinion on the use of virtual reality in general and the NC-VR setup in particular.

3.1. Application Scenarios

Machine Operation

Especially in training of precision mechanics, operating machines is basic knowledge that needs to be learned during vocational training. Usually schools only have one, often older, machine that they can use for training. Using this machine, the teacher can show general aspects of operating this specific machine. When the students are practicing, material is consumed, tools wear and there is a risk of a machine crash or even injuries for the students. To avoid that, the students can use the NC-VR setup to practice operating different machines with different setups without the above mentioned disadvantages. In contrast to existing machine simulators, they can do so by using the real NC control unit and just different virtual, but scale one to one, machine models. Fig. 4 shows the HiL NC-VR coupling as a training scenario. In the foreground is the real NC control unit that controls the virtual machine model in the background.
Virtual Commissioning

A learning objective for e.g. Industrial Electricians is the commissioning of machines. In general, the NC-VR setup (specifically the HiL coupling between the real NC control unit and the virtual machine model) can be used for virtual commissioning of the NC control unit. Because the NC control unit is not connected to a real machine, the commissioning can be carried out in an early production stage of the real machine tool. The VR model has the same axis configuration and work space as the real machine tool. Hence, the commissioning of the NC control unit can be completed even before the real machine tool is available. This saves time as well as production cost.

Using this advantage, the NC-VR setup can also be used for commission training. Not only that, using the virtual model of the machine, all machining processes can be analyzed closely, there is no risk of damaging the machine or causing injuries for the students, while practicing. In addition different error scenarios could be simulated and therefore the problem solving skills of the students can be trained. The capture function of the NC-VR setup can be used to capture the different steps and actions the students did and afterwards discuss that with the teacher to show optimization potentials or possible errors.

NC program simulation and verification

A third application scenario is testing NC programs – hand written or generated using CAM software – always before they are run on the real machine. The simulation with the real NC unit allows the trainees to test their hand-written NC programs on a real NC unit and to see the outcomes at a scale one to one model of the machine tool. This testing can be done without risking a machine crash and without using the capacity of a machine in production. But not only hand-written but also automatically generated programs can be tested – to help the students to learn the handling of the CAM software tools.

One important application is the NC program verification. When a new work piece has to be manufactured, most of the time the CAD model of this work piece is the basis for the manufacturing planning process. This CAD model has to be imported into the CAM software. In the CAM software, the machine-independent Cutter Location Data (CLDATA) file with the milling information will be created. After a conversion from the CLDATA to the NC program via the so-called postprocessor, the NC program is available in a machine-readable format for the first time. The postprocessor is specific to the machine and NC control unit and so is the NC program. The HiL coupling can test this specific NC program at a certain control unit which controls the real machine tool. This is a great advantage compared to desktop-based SiL simulation tools. To verify the
usage of the developed HiL coupling for the NC program verification a NAS 913 approval work piece was used. It is possible to simulate the NC programs in the VR environment by using the elevation grid for the simulation of the material removal as well as the CAD core based offline simulation (see chapter 2.4). Fig. 5 shows the simulation of the milling process of the NAS 913 work piece in the VR simulation environment. Fig. 5 shows the result of the CAD core based offline simulation compared with the real machined aluminum work piece. The number 1 shows a path error coming from the CAM system.

![Fig 5. Generated CAD model from the NAS193 work piece using the sweep volume simulation compared with the real machined aluminum work piece.](image)

The above described NC program verification can be used to discuss with the students the workpieces resulting from their hand-written NC programs – showing possible errors and improvement potentials. All that without using any resources (like material) on the real machine.

3.2. Expert Opinions

Possible Application Scenarios and Advantages

During a workshop with 18 teachers from vocational training schools and colleges, the participants had the chance of a hands-on demonstration of the NC-VR demonstrator (which was one out of four stations). The goal of the workshop was to show the teachers the possibilities of using VR within their normal lessons and to discuss application scenarios and obstacles. In addition to the NC-VR demonstrator, they saw the following applications: VR based maintenance training, using a Microsoft Kinect and a Tablet PC to navigate and interact with the VR simulation of a smart home environment (EU project uTRUSTit) and using VR for marketing models of machines.

After experiencing different application scenarios, the participants sat together in four small groups and discussed the use of virtual reality for vocational training. The participants were heterogeneous group. Most participants were teachers for electronics, NC programming, mechanics and informatics at vocational schools, were the pupils have eight hours class for one or two day per week (on average). The other participants are working at colleges, were classes are fulltime for about six month successively.

Most participants from both groups agreed that the VR technology would, in principle, be a valuable add-on in the didactical tool mix. The two most important criteria for using it successfully would be that the system is easy to handle, both for teachers and students, and that the students can play an active role. So, most of the teacher, would prefer to use the VR technology as a hands-on training tool for their students rather than as a
presentation tool used by themselves. In general there seemed to be three applications that most teachers would be very interested in using. The first is visualization of problems or correlation that cannot be seen in reality, examples being static and dynamic parameters on machine tools, composition of and interaction between materials in material engineering or forces and strain in drawing processes. The second important application is the training of procedures, like assembly or maintenance processes. Therefore it would be important, that errors can be made, will be highlighted and might be corrected during training processes. The third relevant application was said to be the NC-VR demonstrator.

This NC-VR demonstrator could supplement the currently used NC simulation programs. The participants said, that it is especially relevant when used for complex machines and to allow that all self-written NC programs can be tested using the real NC control unit and the scale one to one machine geometry.

**Possible Obstacles and Disadvantages**

Beside all advantages, the workshop participants also saw a couple of obstacles that might impede the use of VR for vocational training. First of all the costs that are still – depending on the desired configuration of the VR system – too high, in most cases. Especially regarding the costs, the NC-VR coupling could be reasonable for schools as it can be established by using a normal 3D TV (or even a normal monitor, although it is no VR anymore), a real NC control unit, which is already available at the school and VR software that is free of charge for education facilities.

The second reservation the workshop participants had were the creation of the VR machine models in addition with the handling of the VR system. They were wondering who could and would create the VR models. Especially the teachers from regular vocational training schools doubted that they would have the time to do that. On the other hand the representatives from the vocational training colleges would see the creation of the VR models as an additional task for their pupils that would in addition train them to use such new technology like VR.

Other possible problems that have been discussed were the handling of the system and the integratability in the existing curriculums. Concerning the handling the following aspects were mentioned as possible obstacles: lack of intuitiveness and too long introduction period; only one student can interact at a time and the others can only watch which might cause the “passive” students to digress. The integration of this new technology in the existing curricula is another challenge. The teachers of the regular vocational training schools consider this the most critical point, as the curricula are already packed with content. The college teachers on the other did see a greater chance.

**4. Conclusion and Outlook**

Overall, the presented NC-VR setup has a lot of application potential in the field of vocational training. The workshop showed that it is (currently) more applicable for colleges than for regular vocational training schools. Nevertheless there is still some work to do before it can be used for educational purposes. First of all it has to be integrated into a didactical concept to include it in existing lessons. Therefore there has to be an easy way to establish the NC-VR setup. In addition the creation of the VR model (most likely from CAD data) has to be quite easy. To solve this challenge, we are currently working on a methods and tools to easily convert CAD data into a VR model, including the automatic transfer of animations and kinematic chains.

Further research regarding NC-VR could be the integration of forces, coming from the chipping process, and the simulation of machine behavior in the real-time simulation.
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