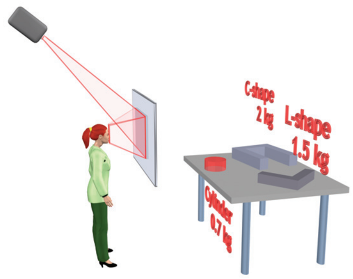
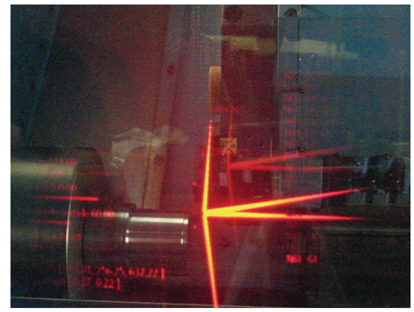
Olwal, A., Gustafsson, J., and Lindfors, C. Spatial Augmented Reality on Industrial CNC-Machines.
Proceedings of SPIE 2008 Electronic Imaging, Vol. 6804 (The Engineering Reality of Virtual Reality 2008), San Jose, CA, January 27-31, 2008.

Spatial augmented reality on industrial CNC-machines

Alex Olwal[*a], Jonny Gustafsson[b], Christoffer Lindfors[b]
[a]School of Computer Science and Communication, KTH, 100 44 Stockholm, Sweden
[b]School of Industrial Engineering and Management, KTH, 100 44 Stockholm, Sweden





ABSTRACT

In this work we present how Augmented Reality (AR) can be used to create an intimate integration of process data with the workspace of an industrial CNC (computer numerical control) machine. AR allows us to combine interactive computer graphics with real objects in a physical environment — in this case, the workspace of an industrial lathe. ASTOR is an autostereoscopic optical see-through spatial AR system, which provides real-time 3D visual feedback without the need for user-worn equipment, such as head-mounted displays or sensors for tracking. The use of a transparent holographic optical element, overlaid onto the safety glass, allows the system to simultaneously provide bright imagery and clear visibility of the tool and workpiece. The system makes it possible to enhance visibility of occluded tools as well as to visualize real-time data from the process in the 3D space. The graphics are geometrically registered with the workspace and provide an intuitive representation of the process, amplifying the user's understanding and simplifying machine operation.

Keywords: ASTOR, augmented reality, mixed reality, CNC, optical see-through, spatial augmented reality, autostereoscopic display, holographic optical element

1. INTRODUCTION

Industrial machines have become advanced tools where automation and advanced feedback is made possible through dedicated control computers. The computers allow us to fully or partially automate complex procedures and can help make manual control more secure and precise. Real-time data from the process is available and many parameters can be interactively controlled through the computer interface. Automation can also allow an operator to monitor multiple machines simultaneously, reducing the number of required personnel for a machine pool.

Many critical procedures exist, however, that cannot be completely automated. In such cases, the operator might need to be able to visually follow and interactively control parts of the current operation, while simultaneously monitoring numerous rapidly changing parameters.

The control computer often has access to a large amount of process information and we can expect this to increase as the systems become more sophisticated and complex. It is thus important that the data is clearly presented and easily accessible, in order to avoid unnecessarily attention-demanding interfaces and information overload for the user.

[*] alx@csc.kth.se; phone +46 8 790 78 85; fax +46 8 24 77 84; http://www.csc.kth.se/~alx/

Today's control computers typically present their data on a traditional computer display and often use a keyboard/mouse or a touch-screen as input devices. The operator observes the process through the machine's safety glass, while using a computer to the side for control and feedback. This setup results in divided attention if the operator has the need to both follow the procedure visually and simultaneously monitor important values on the computer display. While this problem can in part be addressed through display placement, it inherently separates the process data from the process itself.

In this work our goal has been to integrate the process data with the workspace behind the safety glass using Augmented Reality (AR). AR[1] allows us to combine interactive computer graphics with real objects in a physical environment, such as the workspace of an industrial machine. We find it particularly suitable for today's increasingly complex industrial machine processes as it enables intuitive representation and real-time visualization of relevant information in the right place. There are several situations where it might be advantageous to have the capability of annotating the real process with virtual information. An operator might for example want to indicate or emphasize locations inside the workspace behind the safety glass to a co-worker or a student. The type, dimensions and state of the tool currently in operation may be indicated by a virtual label. Process simulation in the real machine using virtual tools and virtual materials could increase safety through virtual previews of the procedure, and provide implicit visual warnings from unintentional geometrical inconsistencies.

We discuss Related Work in Section 2, and describe the industrial machine and our ASTOR system in Sections 3 and 4, respectively. The potential of data visualization in the workspace and our implemented functionality is provided in Section 5, followed by Future Work and Conclusions in Sections 6 and 7.

2. RELATED WORK

The ideal augmented reality interface integrates computer graphics with a real environment seamlessly and without encumbering technology. The long tradition of mobile AR systems[1,2] has however required systems based on head-mounted-displays (HMD) that involve complex tracking and complicated equipment worn by the user. The popularity of video see-through systems can be attributed to the relative ease of implementation and rapid prototyping possibilities provided through various software libraries, such as ARToolKit[2]. The more direct optical see-through approaches have numerous advantages, since many applications cannot accept the indirectness of video see-through and its associated downsampling of the real environment.

The emerging field of spatial AR, where the display is placed in the environment instead of worn by the user, demonstrates how spatial optical see-through and spatial projection systems can be more suitable than the dominant HMD-based AR. Bimber and Raskar[4] mention limited field-of-view, resolution, registration and bulkiness as examples of issues that make HMDs less attractive in AR applications that need not be mobile.

They also address a vast set of technical problems that are involved in the implementation of the various presented spatial AR systems[4]. The Virtual Showcase[5], The Extended Virtual Table[6] and Transflective Props[7] are all inspiring spatial optical see-through AR setups where large half-silvered mirrors are used as optical combiners. These semi-transparent mirrors however have a disadvantage in the need to reflect the image from a secondary display, and their inevitable reduced brightness for the reflected graphics and the real environment due to the ratio of reflected and transmitted light. Half-silvered mirrors also impose limitations on the display-mirror configuration and possible viewing directions. Transparent screens, such as an LCD with the backlight removed, can also be employed, as described by Schwald et al.[8]. The LCD, however, not only creates the image in the plane of the display, such that graphics and the real environment must always be physically separated, but also prohibits the use of autostereoscopic technologies, as they would optically distort the scene seen through the LCD. Another example of a system with similar limitations is presented by Hirakawa and Koike[9], in which a transparent film is used. Autostereoscopic setups have been used in "reach-in" configurations where reflected imagery appears co-located with the user's hand while it manipulates a haptic device[10]. These setups also use semi-transparent mirrors and suffer from the previously mentioned limitations.

Spatial AR systems that are based on a digital projector registered with the environment, allow the projection of annotations and augmentations directly onto the physical objects[4]. This removes the need for a special optical combiner and makes it possible to in the most non-intrusive way alter the appearance of objects or annotate the real environment. A critical limitation is the requirement of a suitable projection surface and the inherent inability to render 3D graphics in mid-air without the use of additional optical aids.

Industrial AR projects include both HMD- and spatial display-based approaches[12,13,14,15,16]. The development and modification of programs for robot control is a particularly suitable application, where the operator has the task of specifying the robot's motion sequence. The established *continuous path*, *point-to-point*, or *teach-in* methods[17] are demonstrative techniques in which the operator moves the robot along a planned path and records point coordinates. Skourup and Pretlove[17] discuss the problem of online robot and CNC (computer numerical control) machine programming with its typical lack of visual feedback and requirement of highly skilled personnel. Pettersen et al.[15] describe an HMD-based system for visualizing results during paint robot programming, while Zaeh and Vogel[13] present a system using 3D laser projection for manipulating trajectories directly on workpiece surfaces. Both projects report that visual feedback from the use of AR reduced programming time by 80% in their experiments.

Numerous researchers mention the importance of ergonomics, uncomplicated calibration, visual quality and adequate precision in industrial environments[12,13,14], which makes HMDs, video see-through techniques and mobile solutions less attractive in a stationary industrial setup. While 3D laser projection is promising in the augmentation of 3D surfaces[13], direct projection is less applicable in the workspace of a CNC machine, since the tool and the workpiece are moving in free space, leaving virtually no room for suitable projection surfaces.

3. INDUSTRIAL CNC LATHE

We use an SMT Swedturn 300 industrial lathe[18] in our current setup, which is controlled and interfaced through a Siemens 840D control computer, as shown in Figure 1. The production engineers typically design the manufacturing process using CAD/CAM (computer assisted design/manufacturing) software on a designated PC. When the desired procedure is completed, a CNC (computer numerical control) program is exported, which specifies a sequence of movements for the machine tool and thus directly control the operation of the lathe. Once loaded onto the control computer, the operator runs the program, but can still interactively manipulate execution speed (speed of movement) or pause/resume the program, for instance.

3.1 Online programming

During design of new operations, the operator might make changes to the program on the control computer, or even write a new program directly on the machine. In these situations, the program is often tested by running the machine using the real tool in place, but with the workpiece removed for safety reasons. This iterative process provides no visual feedback and requires that the operator is an experienced CNC programmer.

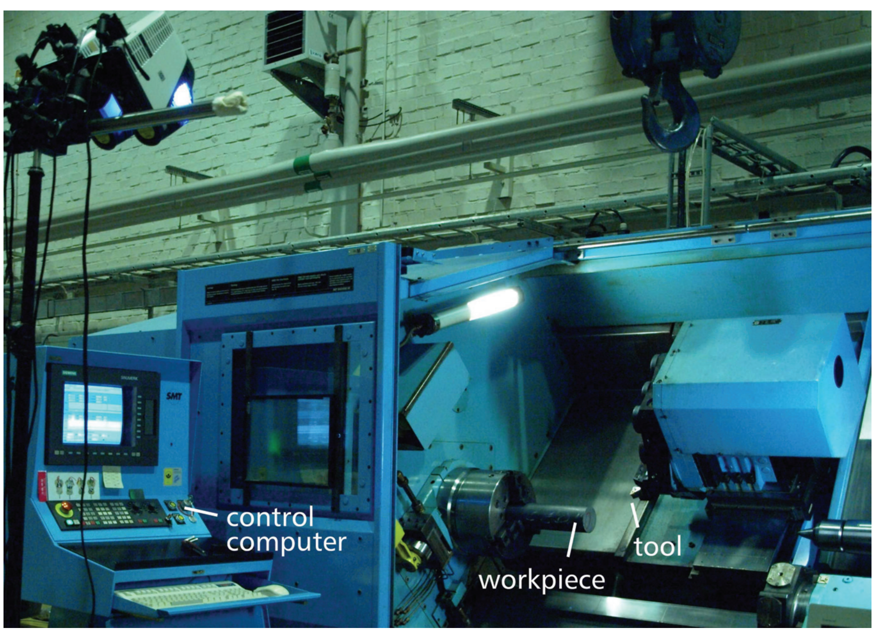


Figure 1. Industrial lathe (SMT Swedturn 300) with control computer (Siemens 840D). The machine doors are opened such that the tool and workpiece can be clearly seen.

3.2 Real-time data

While the program is running, the control computer provides real-time access to relevant measurements from the process, such as tool position and orientation, RPM (revolutions/minute), temperatures, current operation and other values of interest to the operator. Additional sensors for measuring power, torque, forces and vibrations, for example, can often be installed in the industrial machines[19], if not originally present. In our setup, a dynamometer for measuring forces on the tool tip is installed. One application of real-time force measurement is the possibility to adaptively adjust the power of the machine, such that the lifetime of the tool can be maximized and tool breakage can be automatically detected[20, 21].

3.3 Communication

The SMT Swedturn 300 employs a control system that runs on an older Windows version and has limited means for external connectivity. It does however support Dynamic Data Exchange (DDE), a legacy protocol for inter-application communication. We make use of NetDDE, which enables DDE communication over the network, to access the measurements in the system. As DDE/NetDDE is no longer officially supported in recent versions of Windows, we use an older Windows computer as a dedicated NetDDE proxy. A custom program handles the NetDDE communication with the lathe's control computer, while streaming measurement data over UDP to subscribing machines on the network.

4. THE ASTOR SYSTEM

The ASTOR system[22] is a novel spatial augmented reality system. In contrast to previous work, it enables:

- autostereoscopic 3D graphics
- flexible projection and viewing angles
- bright imagery
- highly transparent see-through

4.1 Display system

One of the main requirements for AR is the ability to blend the user's view of the real environment with overlaid virtual imagery. In our autostereoscopic, optical see-through system setup, we use a 30×40 cm holographic optical element[23,24,22] (HOE) overlaid onto the machine's safety glass as the optical combiner, which allows us to simultaneously

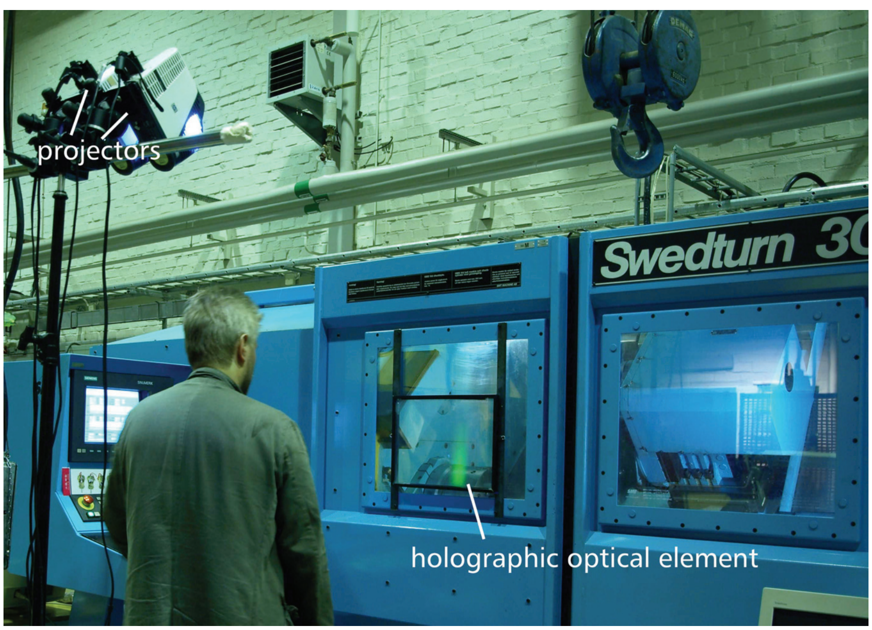


Figure 2. The operator views the machine operation through the holographic optical element (HOE), which is illuminated with stereoscopic images from the projectors driven by a PC. The setup allows 3D annotation to appear in the workspace, augmenting the operator's view of the process with relevant information.

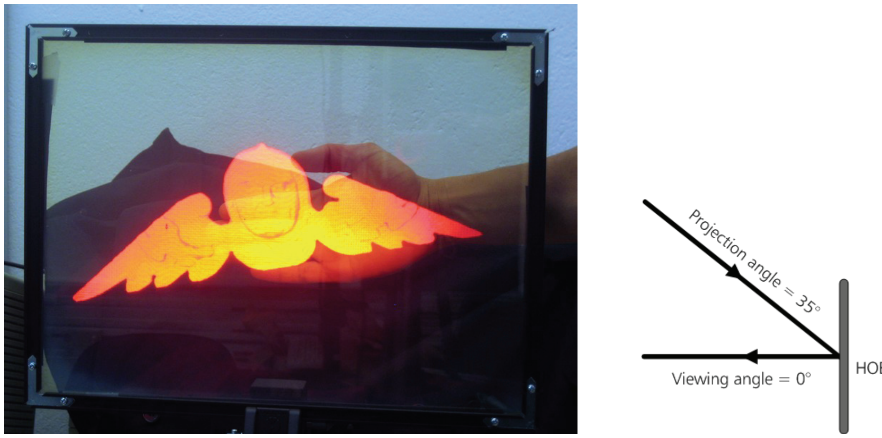
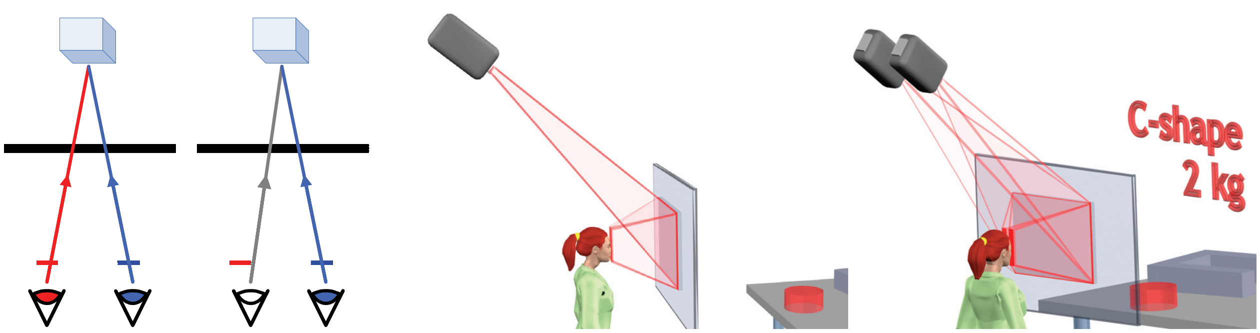


Figure 3. The optics in the current holographic optical element (HOE) were optimized for an augmented reality setup, with viewing and projection angles suitable for projection from above and clear visibility when the user looks straight through the display.

see the real environment, as well as superimposed 3D graphics, when we look through the transparent display. (See Figure 2.) We manufactured an HOE that can be viewed perpendicularly to its surface while the images are projected in reflection from an angle of 35 degrees above this line of sight. This avoids disturbing direct reflections from the projectors and allows the user to look straight through the display. (See Figure 3.) Illuminating the HOE in reflection leaves the space studied completely undisturbed by optical equipment. The projectors will also be protected from the dirty and hazardous environment that exists inside the industrial machine, which is a critical requirement for industrial applications.

The HOE restricts the viewing angle of the image vertically and horizontally, such that each projector creates a real image of a thin vertical slice, floating in space in front of the HOE plate. The image from the projector can only be seen from within this slice. Since the slice has a width of 50 mm, the image can only be seen by one eye at a time. This allows us to place two projectors horizontally that create two horizontally separated off-axis projections. Each projection can be seen by a single eye when it is looking through the viewport defined by the corresponding slice, as shown in Figure 4. Autostereoscopy is achieved by rendering a stereo pair to the projectors. The setup can be extended through additional projectors at corresponding angles; four projectors would for instance provide three stereo pairs, hence expanding the available viewing volume in which the viewer may move.

The HOE provides monochromatic, yet bright, overlaid 3D graphics without the need for special glasses, as well as a direct and clear view of the real environment behind the display. We leave out the specifics on the HOE, as it has been described in detail in previous work[23, 24, 22].



(a) (b) (c) (d)

Figure 4. Transparent autostereoscopy for augmented reality. a) When both eyes look through the thin slices created by the two reflected projections, individual images are seen, and an autostereoscopic effect can be achieved. b) If the eye is however outside the slice, no image will be seen. c) Due to the transparency of the display, it allows the user to see both the stereoscopic images and the real environment behind it. d) This makes it possible to annotate or augment physical objects in the environment with 3D graphics.

We currently use HP mp3135 projectors (1800 ANSI lumens, 2000:1 contrast ratio) with a native resolution of 1024×768 pixels. The standing projector model is desirable in our setup since it allows the projectors to be mounted very close to each other. The HOE has the ability to create extremely bright graphics given that the majority of the light from our 1800 ANSI lumen projectors is reflected through a very limited area in space.

4.2 Input and Rendering

The application server is implemented in C++ and OpenGL. Process data from the industrial machine is received through the NetDDE proxy over UDP (See Section 3.3) and is used to update the internal state of the application.

In the case of a single stereo perspective using two projectors, we can drive the digital projectors from one PC with a dual-head graphics card. The graphics card can be configured to a 2048×768 virtual screen which spans the two physical ports on the card, which are connected to two projectors. By setting up two 1024×768 viewports in OpenGL, we can render the left and right perspectives to different parts of our virtual screen. We set the projection matrix in OpenGL to the corresponding skewed frustum before rendering the graphics for each of the two perspectives.

Our architecture naturally allows multiple PCs to be employed, since each of them can receive UDP data over the network from the industrial machine and drive one or more projectors. This capability is especially useful in the case of more than two projectors, or when PCs with a single video output are employed, such as laptops or computers with less sophisticated graphics cards.

For user interaction with the application, we provide support for various game controllers. Since they have specifically been designed for freehand use in mid-air, they are well-suited for interaction at our industrial machine. The controllers make it possible to indicate 3D positions inside the workspace, as well as choose among different options in the applications.

Our two-projector setup is driven by a dual Xeon 3.0 GHz PC running Windows XP, with an NVIDIA QuadroFX 500 graphics card. The system architecture is shown in Figure 5.

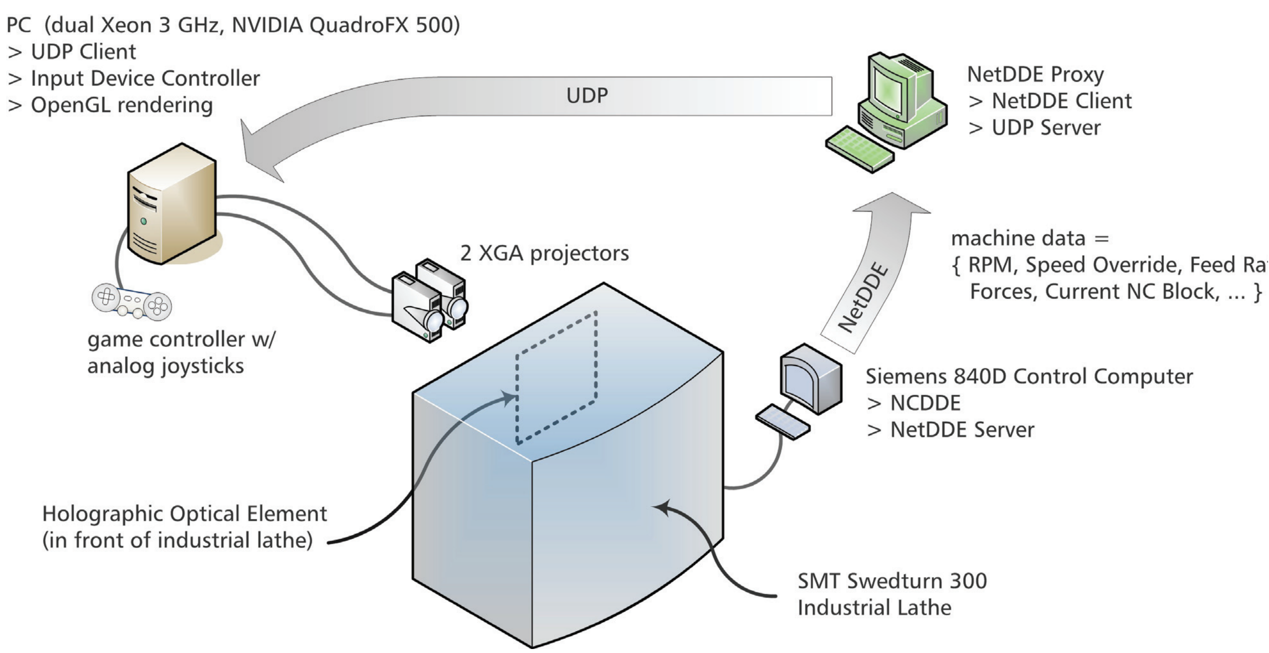


Figure 5. System architecture. The industrial machine's control computer communicates over the legacy NetDDE protocol to our NetDDE proxy. The proxy relays the data over UDP to our application server, which renders the stereo perspectives and handles input from a game controller. It drives to projectors, which create the 3D images on the holographic optical element.

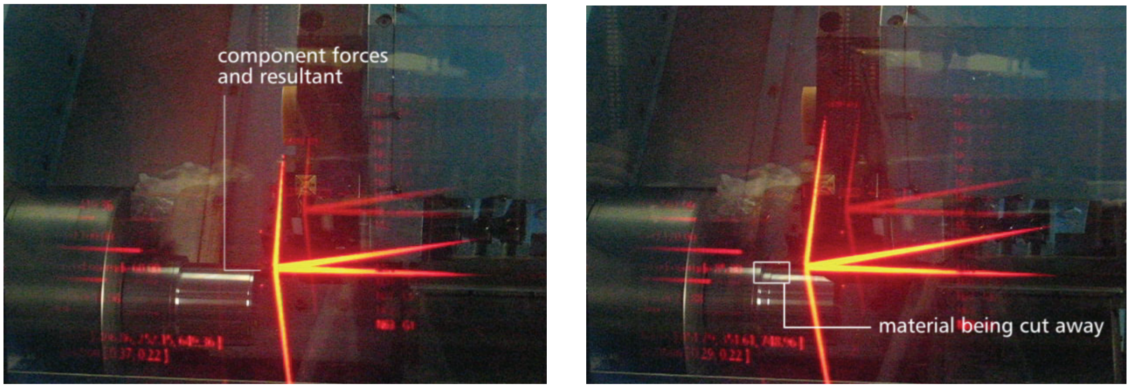


Figure 6. View of the workspace through the HOE overlaid on the safety glass. Our system allows us to visualize real-time force data on the tip of the machine tool and overlay it onto the view of the real machine tool and workpiece using bright monochromatic, red graphics.

5. INTEGRATED DATA VISUALIZATION

The ability to provide real-time visual feedback to the operator is specifically useful when the operator designs a new program or modifies existing ones. Experimentations and research with different tools and materials also benefit from a better understanding of the current state of the operation. The visualization of process data directly in the workspace reduces mental load for the operator and provides intuitive access to the information.

5.1 Enhanced visibility

One particularly interesting property of AR is the ability of reducing the impact of occlusion and enhancing the visibility of real world objects. In the case of industrial processes, it might be difficult to see the tool as it for some operations is very small or is cutting behind or inside the workpiece. Particles, such as swarf or cutting fluids, can also reduce the visibility, and in the case of cutting with a water jet, there is no physical tool at all. The ability to render bright 3D graphics at any location in the workspace makes it straightforward to indicate the tool position at all times.

5.2 Real-time 3D parameter visualization inside the workspace

The computer graphics makes it possible to provide visual renderings of process data from sensors in the machine (See Section 3.2). Measured values that have natural graphical representations, might be especially advantageous to visualize in 3D in the workspace. Critical sensor events could leave traces in 3D space, visually indicating the magnitude of the sensed parameter and the location and time at which it occurred.

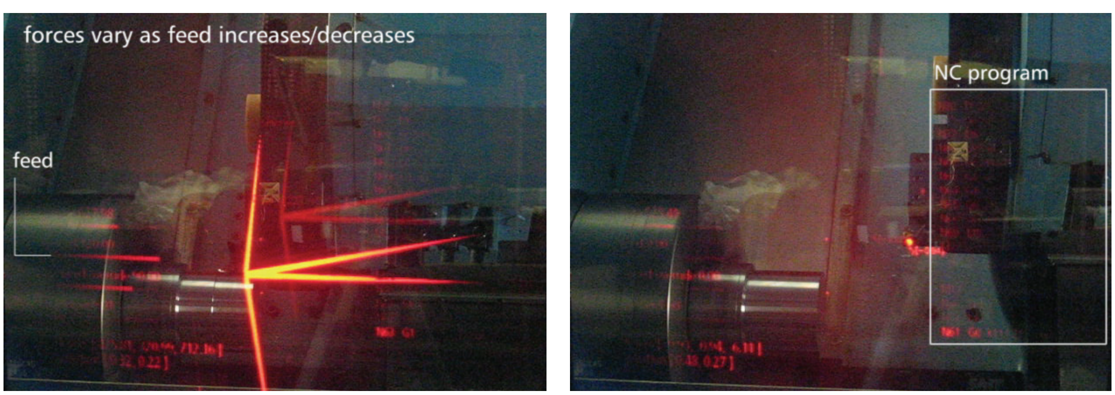


Figure 7. View of the workspace through the HOE overlaid on the safety glass. We also visualize other relevant information using 2D overlays. Left: 2D charts indicate feed, power, speed override, feed and RPM graphically. Right: The progress of the machine program instructions can be seen during operation.

In our system we visualize the forces from the dynamometer on the tool tip, using 3D force vectors for the three components and the resultant, as shown in Figure 6. We also provide a 2D overlay with charts for power, speed override, feed and RPM in the machine to the left, and the NC operations on the right hand side. (See Figure 7.)

Providing sensor visualization can make a significant difference, for example in the event of tool breakage during an internal operation. If no means for automatic handling of problems is available, the machine will continue to push into the material. It is not uncommon that this results in deformation of the machine, requiring exhaustive alignment and calibration procedures, if not demanding replacement and repair of parts.

6. FUTURE WORK

As in the case of robotics[13], interactive visual feedback would be primarily of interest for production of limited series when online programming and frequent redesign are used. We have also identified the benefit of our technology in training and education.

6.1 NC interpreter and simulator

In the current system we merely highlight the current NC operation, but in the future, an NC interpreter could analyze the motion sequence of the tool, and allow the system to support a set of interesting features. The operator would for example be able to simulate the process with a virtual tool and real workpiece, real tool and virtual workpiece, or with both a virtual tool and virtual workpiece. This could be powerful in online programming, providing a safe and direct mechanism for iterative program development with real-time visual feedback. The simulator would also save time since the operator could jump to any part of the program, having the ability to fast forward or reverse the process.

The interpreter would be useful for real-time operation, making it possible to visually indicate the past and future trajectory of the real tool using motion vectors. The operator could thus easily see the tool's expected position, for example in 5, 15 and 45 seconds ahead of time. By visualizing the complete tool trajectory of the program, we could increase safety, by visually making sure that the tool does not exceed any geometrical bounds.

6.2 Training and education

The interpreter would be relevant also for training purposes, allowing students to safely learn the operation and programming of the industrial machines. The simulator would naturally allow virtual experiments with combinations of exclusive tools and expensive materials without the need for destructive and costly processes. Although much of the simulation can be done today on CAD/CAM workstations, the simulation of the real process using real machine controls (but with virtual tools and materials) is important for realism and development of practical skills.

7. CONCLUSIONS

In this paper, we have presented how our spatial AR system, ASTOR, can be used to render virtual 3D imagery that visually appears inside the workspace of an industrial CNC machine, geometrically registered with the tools, workpiece and workspace. By using a large holographic optical element, overlaid onto the safety glass, we create an unobtrusive solution that does not rely on user-worn equipment, such as HMDs or sensors for tracking. The transparency of our display system simultaneously allows the operator to clearly see the real machinery in the workspace, making it possible to overlay visualizations from process data over the tools and workpiece, amplifying the user's understanding and simplifying machine operation.

Our solution works as a software and hardware plugin and requires minimal modifications to the existing machine. The system requires only an initial manual calibration process of the projectors relative to the HOE and the machine, and these components are expected to be rigidly mounted with respect to eachother in a production environment. The software also does not interfere with machine operation, and the modularity of our architecture opens up for other communication protocols, such as OPC[25], a standard for interoperability in industrial automation, allowing us to integrate with other industrial machines.

ASTOR places the process data into the workspace, where it belongs, and simplifies machine operation and programming for both novices and experts. Autostereoscopy and optical see-through ensures that it does not alter the existing process, but merely adds visual feedback into the existing real-world view, to augment and empower the operator's senses.

8. ACKNOWLEDGEMENTS

We thank Dr Mats Bejhem, Jan Stamer, and Professor Mihai Nicolescu for invaluable discussions, suggestions and technical assistance with the industrial lathe.

REFERENCES

1. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S. and MacIntyre, B., “Recent Advances in Augmented Reality,” IEEE Computer Graphics and Applications 25(6), 24-35 (2001).
2. Feiner, S., MacIntyre, B., Höllerer, T., and Webster T., “A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban environment,” Proc. ISWC '97, 208-217 (1997).
3. ARToolKit, http://www.hitl.washington.edu/artoolkit/, January 2008.
4. Bimber, O. and Raskar, R., “Spatial Augmented Reality – Merging Real and Virtual Worlds,” A K Peters, ISBN 978-1-56881-230-4 (2005).
5. Bimber, O., Fröhlich, B., Schmalstieg, D., and Encarnação, L.M., “The Virtual Showcase,” IEEE Computer Graphics & Applications 21(6), 48-55 (2001).
6. Bimber, O., Encarnação, L.M. and Branco, P., “The Extended Virtual Table: An Optical Extension for Table-Like Projection Systems,” Presence: Teleoperators and Virtual Environments 10(6), 613-631 (2001).
7. Bimber, O., Encarnação, L.M., and Schmalstieg, D., “Augmented Reality with Back-Projection Systems using Transflective Surfaces,” Proc. EUROGRAPHICS 2000 19(3), 161-168 (2000).
8. Schwald, B., Seibert, H., and Weller, T., “A Flexible Tracking Concept Applied to Medical Scenarios Using an AR Window,” ISMAR'02, 261-262 (2002).
9. Hirakawa, M. and Koike, S. A, “Collaborative Augmented Reality System using Transparent Display,” Proc. ISMSE'04, 410-416 (2004).
10. Reachin, http://www.reachin.se/, January 2008.
11. SenseGraphics 3D-MIW, SenseGraphics. http://www.sensegraphics.com/, January 2008.
12. Pentenrieder, K., Bade, C., Doli, F., and Meier, P., “Augmented Reality-based factory planning - an application tailored to industrial needs,” Proc. IEEE and ACM ISMAR 2007 (IEEE and ACM International Symposium on Mixed and Augmented Reality), 31-39 (2007)
13. Zaeh, M.F., Vogl, W., “Interactive laser-projection for programming industrial robots,” ISMAR 2006, IEEE/ACM International Symposium on Mixed and Augmented Reality, 125-128 (2006).
14. Bischoff, R., Kazi, A., “Perspectives on augmented reality based human-robot interaction with industrial robots,” Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004) 4, 3226-3231 (2004).
15. Pettersen, T., Pretlove, J., Skourup, C., Engedal, T., Lokstad, T., "Augmented reality for programming industrial robots,". Proc. Second IEEE and ACM International Symposium on Mixed and Augmented Reality, 319-320 (2003).
16. ARVIKA, http://www.arvika.de, January 2008.
17. Skourup, C., Pretlove, J., “Intuitive robot programming based on operators' implicit knowledge”, Proc. IEEE International Conference on Systems, Man, and Cybernetics 2, 702-705 (2001).
18. SMT Swedturn 300 Technical Specifications, http://www.smtswedturn.se/se/st300.html, January 2008.
19. Montronix Tool and Process Monitoring Sensors, http://www.montronix.com/, January 2008.
20. Bejhem, M., “Machining Monitoring and Control Based on Parametric Modelling,” PhD dissertation, Royal Institute of Technology, Dept. Production Engineering, TRITA-IIP-01-19 (2001).
21. Omative Adaptive Control and Monitoring, http://www.omative.com/, January 2008.
22. Olwal, A., Lindfors, C., Gustafsson, J., Kjellberg, T., and Mattson, L., “ASTOR: An Autostereoscopic Optical See-through Augmented Reality System,” ISMAR ’05, 24-27 (2005).
23. Gustafsson, J. Lindfors, C., “Development of a 3D Interaction Table,” Proc. SPIE 5291, 509-516 (2004).
24. Gustafsson. J. Lindfors. C. Mattsson, L. Kjellberg, T., “Large Format 3D Interaction Table,” Proc. SPIE 5664, 589-595 (2005).
25. OPC, http://www.opcfoundation.org/, January 2008.