CUSTOMIZABLE CAPACITIVE SENSOR SYSTEM USING PRINTED ELECTRONICS ON WINDOW GLASS

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ABSTRACT
Printed electronics offer new possibilities in the design of footprints and integrated mechatronic systems. Fast and uncomplicated customization and cost-efficient fabrication are further benefits of this technology. In combination with other production processes like pick-and-place systems or fused filament fabrication (FFF), functional applications like communication or sensing devices can be produced in a very flexible way.

The authors demonstrate how to produce a capacitive sensor system on three millimeter window glass by combining the piezo-jet technology and a pick-and-place system within a single five-axis CNC machine. The piezo-jet system is used to produce the circuitry by printing silver micro paste onto the glass plate. The process is maskless, works with a standoff-distance between one and ten millimeters and can process inks and pastes with a viscosity from 50 mPas to 200,000 mPas. The pick-and-place system puts all necessary surface mounted devices (SMD) directly onto the liquid paste which contains adhesives. The only process that takes place outside the machine is the sintering. However, by integrating an ultra violet (UV) or near infrared (NIR) curing system this process step could also be carried out within the machine. After the sintering the system is fully functional and does not require any further post-processing.

The system consists of a micro-controller, two capacitive proximity detection ICs, resistors and capacitors. The digital outputs of the sensors could be used to control any given application, for reasons of illustration the functionality of the system is shown by an additionally mounted LED-strip. The system is easy to design and quick to adapt since the electronic layout is based on the standard layout of the IC-provider and the used software uncomplicated and open-source.

Due to the placement at the back of the glass the system is perfectly protected against mechanical and chemical influences. It detects all kind of materials so the sensors can be triggered while wearing gloves or by people with a hand prosthesis. Moreover, the sensitivity can be easily adjusted over the software of the microcontroller which makes the application easy adaptable to several conditions. By recognizing different touch patterns, different operating modes can be performed. Currently the sensor system works as a touch switch, but it could also be adapted to realize a low-cost distance sensor.

The flexibility of the used five axis system in combination with the high standoff-distance of the piezo-jet print head offers the possibility to print such systems on a wide spectrum of three-dimensional bodies. Even printing around or into corners is possible. With this method existing components can be functionalized electronically without having to redesign them. The produced demonstrator shows the possibility to extend a component by operating elements, but the capabilities go much further. Existing components can not only be extended by numerous sensor functions, communication elements such as Bluetooth or W-Lan antennas can also be realized in this way.

Key words: printed electronics, sensor system, capacitive, manufacturing process

INTRODUCTION
A lot of research focuses on applications for printed electronics using digital printing processes. One of the main advantages of those processes is the high flexibility as no masks are used. Thus a given design can be implemented with very little preparatory work. Additionally, processes with a certain standoff-distance offer the benefit of enabling printing on a wide scope of freeform parts.

The demonstrator described in this paper is a basic use case. It shows how the combination of a piezo-jet process and a pick-and-place system within a five axis CNC machine provide the basis for manufacturing a customizable, low cost sensor systems on a given substrate. For reasons of better visibility, the system is printed on window glass. Thus the circuit layout and the attachment of the parts are clearly visible. Furthermore, this material is low cost and easy to acquire.

BACKGROUND

The first attempts to print electric circuits using conductive ink were made more than 30 years ago [1]. Today there is a wide variety of processes for the application of printed electronics, traditional printing processes like intaglio or screen printing and digital printing processes like Ink-Jet or Aerosol-Jet techniques. The constant progress in research and development on those technologies leads to several fields of application and to increasing qualities. In combination with other technologies like pick-and-place systems or additive manufacturing methods like FFF, mechatronic integrated devises (MID) can be manufactured using only a comparably short process chain [2–4]. A great example of the possibilities that the combination of different additive manufacturing technologies provides is the production of a mechatronic devise in a single machine [5].

Piezo-Jet-Printing

Piezo-jet printing is an ink jet technology relying on the drop on demand principle. The ink containing cartridge is connected to the print head. Pressurized air is applied to the end of the cartridge and presses the ink into a reservoir within the print head. There a heating element adjusts the viscosity of the ink. A tapped driven by a piezo actuator is placed above the outlet of the printing nozzle. When voltage is applied to the piezo actuator, the tapped is pushed down into the nozzle and presses out an ink droplet. [6, 7]

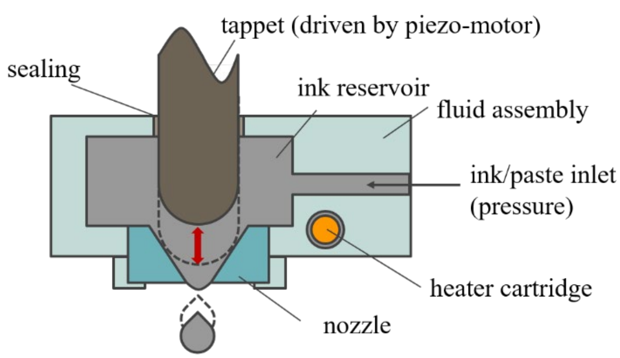

Figure 1. Function of the piezo-jet print head [7]

Pick-and-Place System

Pick-and-place systems are commonly used in the printed circuit board (PCB) assembly to pick electronic components from a tray or tape feeder and place them on the PCBs. Additionally, cameras and image detection software can be used to detect the part and the PCB as well as their offset and rotation. Even an in-situ process inspection of printed electronic circuits on an additively manufactured object is possible with such camera systems [8].

Process Combination

The combination of a digital printing process and a pick-and-place process within a single five axis CNC machine enables the manufacturing of functional electronic systems on a wide variety of freeform parts. This allows to automatically extend the functionality of existing devices.

HARDWARE

The utilized system is a five axis CNC machine. It has three linear axes X, Y and Z with a moving range of 400 mm, 300 mm and 140 mm. The X-axis is installed at the back of the machine, the Z-Axis is mounted on the X-Axis and the Y-axis is located at the basis of the machine. The Y-axis moves the swivel unit which contains an A-axis that rotates around X and a B-axis that rotates around Y. While the A is limited to a 180-degree rotation, the B-axis is only limited by the overrun of the encoder memory, which means several hundred rotations. This setup allows to print on and to additively manufacture, a great number of 3D structures, like egg shaped timers [5] or helix antennas [9].

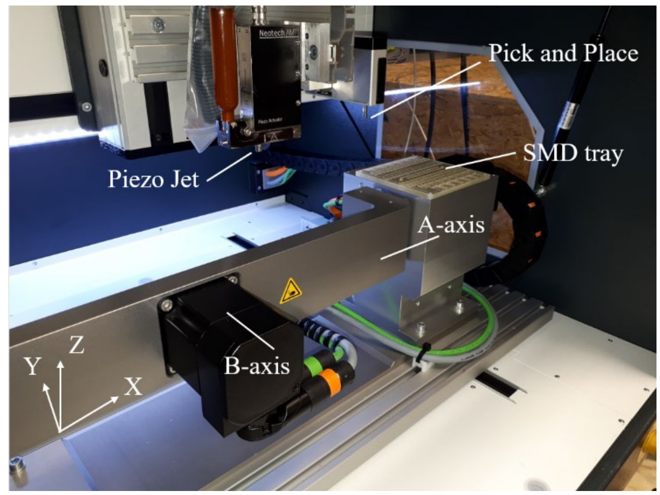

Figure 2. Setup of the five axis machine

The picture above shows the setup of the machine. The demonstrator described in this paper was manufactured on a metal plate which then was mounted on the lever of the A-axis.

DEMONSTRATOR

The demonstrator is built on a piece of window glass with a length of 200 mm a height of 100 mm and a thickness of 3 mm. The material properties of the glass were not investigated.

The electronic components consist of a microcontroller, two capacitive touch ICs, four capacitors and nineteen resistors. For handling reasons, resistors and capacitors were used as SMD parts in size 1206, a size that is suitable to handle with the utilized systems. The capacitive touch ICs are in a SOT-23 package with a pitch of 0.95 BSC, the microcontroller in a SO8 package with a pitch of 1.27 BSC.

The LED strip consists out of five RGB LEDs which can be controlled individually via a data bus. Since strips of five LEDs could not be purchased a 70 LED strip was bought and cut into fitting pieces.

Table 1. Bill of Materials

Quantity	COMPONENT
1x	Window glass
1x	Microcontroller (ATTINY 85-20)
2x	Capacitive-Touch-Sensor (MTCH101)
1x	LED-Strip
4x	Capacitor 100 nF
4x	Resistor 4.7 kΩ
2x	Resistor 10 kΩ
2x	Resistor 16 kΩ
11x	Resistor 0 kΩ
	Silver micro paste

Microcontroller

A microcontroller is used to process the sensor signals and control the LED-strip. The proof of concept was done with an external Arduino Uno connected to the sensor system. Several reasons led to the replacement of the external Arduino Uno by a microcontroller mounted on the glass. The first reason was reliability. The first prototype showed that the contact pads for external connection were the main issue. Since soldering onto the utilized silver paste is not possible, clamp contacting was the alternative. Embedding the microcontroller onto the glass plate reduces the number of external contact pads from ten to two. This eliminated eight possible error sources. The second reason was space reduction. The Arduino Uno has a length of 68 mm and a width of 53 mm. The ATtiny SOIC is only 8 mm in length and 5 mm in width. Therefore, the size of the overall system could be drastically reduced.

The experience from the first prototype led to the specification for the microcontroller. At least five pins are needed to control the sensor system. One input for each sensor to gather its state, one output to equally set the sensitivity of both sensors, and two pins for the data bus of the LED strip. Furthermore, the size of the microcontroller should be smaller than 100 mm² but the pitch more than one Millimeter. Therefore, SO8 was a fitting package size. Since the file size of the control program was 7.8 kB, the minimum memory size had to be 8 kB. Considering all these prerequisites, the choice fell on the ATtiny 85-20 SU which fulfilled all requirements.

Circuit Design

The two main guidelines for the circuit design was on the one hand, the layout provided by the supplier of the capacitive touch IC. On the other hand, to have a minimal number of intersections. Since the electric circuit has just one layer, the intersections must be implemented by a non-conductive layer. Practical approaches are either the use of a dielectric coating or the application of zero ohm resistors. Within the current layout capacitors, resistors and the ICs are used to generate intersections.

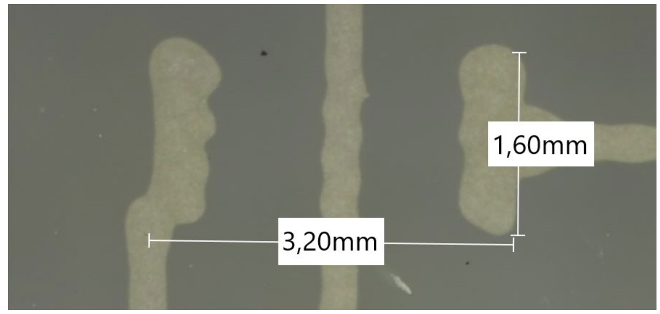

Figure 3. Implementation of an intersection

Figure 3 shows how components are used to create an intersection. Left and right of the crossing line are the contact pads for a type 1206 component. The distance between the pads and the line is big enough to prevent short circuits even if the paste is squeezed when the component is pressed onto the printed tracks.

After the schematic design was done, the machine toolpath for the piezo-jet printing was implemented as a 2D-layout in a CAD-software. Lines were designed as contour elements, which means that the calculated toolpath travels them once. Pads were marked as fill elements. Thus the program calculates the path to fill them automatically.

The whole layout consists of only four elements, straight connection lines, circles to construct the electrodes, rectangular pads with a length of 1.6 mm and a width of 0.4 mm to place the type 1206 components on and squares of 5 mm to clamp on the power source. The small number of elements makes the layout fast and easy to create as well as to adapt.

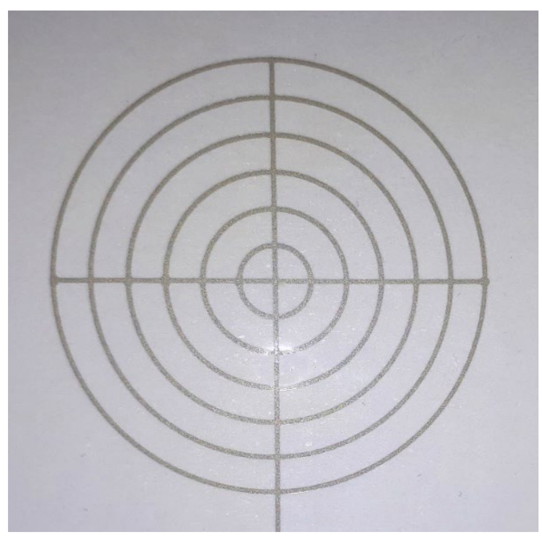

Figure 4. Crosshair design of sensor electrode

To save material, a crosshair design was chosen for the sensor electrode instead of a solid design. The material reduction is calculated after the geometrical characterization of the printed lines.

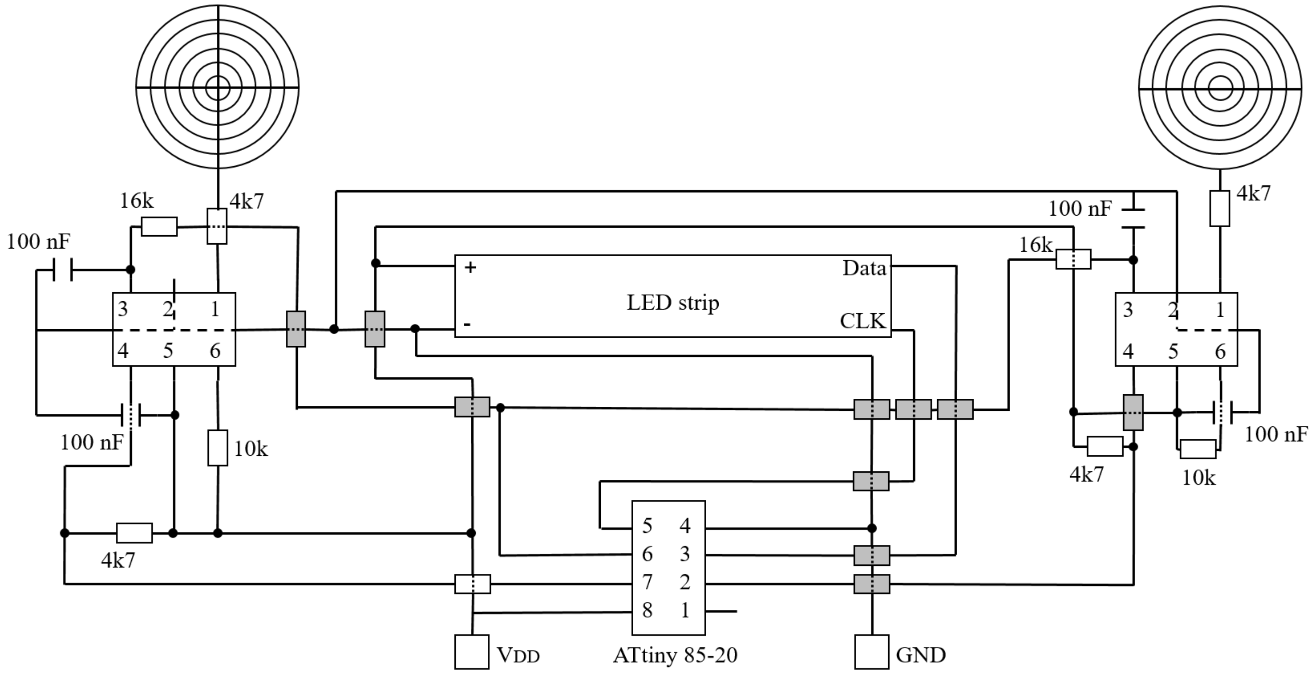

Figure 5. Layout of the sensor system

The figure above shows the layout of the whole sensor system. At the upper left and right corner, the crosshair shaped electrodes can be seen. They are connected to pin 1 of the capacitive touch IC via a 4.7 kΩ resistor. Pin 4 of the IC provides the signal which is connected to the microcontroller. The sensitivity of the capacitive touch IC is adjusted through pin 6 of the microcontroller. The LED strip is controlled via pin 5 and 3. All grey resistors are zero ohm and are just used to enable intersections.

Piezo-Jet

The piezo-jet printing was done using an ink that contains micro scale silver particles. Due to the high viscosity of roughly 26,000 mPas, the paste does not dissolve on the glass and produces precise outlines. The distance between nozzle and glass was around 2 mm. Higher working distances are possible but would lead to a reduced printing quality because a higher overspray occurs.

Pick-and-Place

After the printing of the layout the electronic components were placed directly onto the liquid paste. A little spring within the pipette of the pick-and-place head ensures that the components can be pressed onto the paste without damaging the substrate, the pick-and-place system or the component. Nevertheless, the pressure applied by the tooltip is strong enough to attach the components to the subtrate.

Since the camera system in the utilized machine cannot yet detect the rotation of picked components, they had to be aligned very accurate in the corners of the tray. The glass plate was aligned at a rectangular metal frame. With those supporting measures a sufficiently precise placement could be achieved.

Curing

According to the supplier recommendations, all printed structures were cured in a convection oven first at 60°C for 10 minutes and afterwards at 110°C for 10 minutes. Curing in two iterations is necessary for structures with a layer thickness greater than 20 µm to prevent stress breaks. The storage temperatures of all utilized components is above 150°C so the curing temperature does not affect them.

Connection of the LED strip

Since the RGB LEDs are soldered onto a plastic strip and have to be mounted upside down, the connection is not as trivial as the connection of the other components. When the LEDs are placed on the glass a distance of 1.4 mm between printed line and the connection point at the plastic strip must be bridged.

In a first step the LED strip is fixated on the glass plate using two a component epoxy resin. Afterwards the resin was cured in a convection oven to achieve its strength. Afterwards copper wires with a diameter of 200 µm were pulled through little holes in the plastic strip and then twisted and bend so it would lie on the printed line. Then conductive adhesive was applied using a pneumatic dispenser. In the last step the demonstrator was cured in the convection oven a third time to solder the conductive adhesive.

The results can be seen in Figure 6. Not only the connections are looking unprofessional. Also placing the strip on the glass needs a steady hand and every unwanted movement leads to unpleasant resin residuals on the glass. Compared to the other steps, the connection of the LED is a huge effort and offers a lot of potential for improvement.

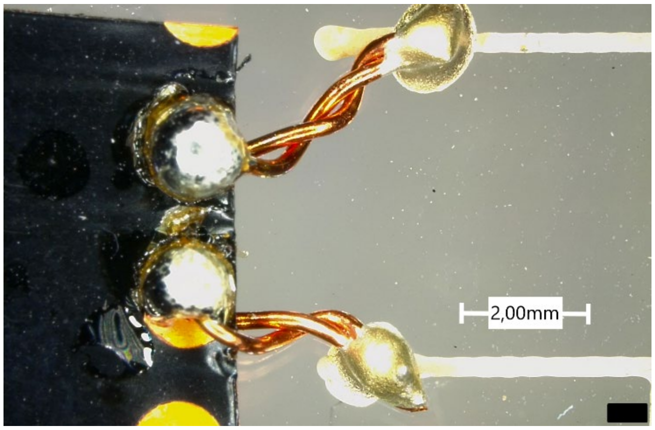

Figure 6. Connection of the LED strip via twisted wires

Software Design

A logic was programmed process the signals delivered by the capacitive touch ICs. According to the input signal the number of LEDs on the LED-strip increases or decreases. Furthermore, the logic is able to distinct between a long and a short touch. While short touches alter the number of active LEDs, long touches alter the color of the LEDs or switch the system to stand-by-mode.

Apart from two imported libraries the source code contains less than 200 lines and has a size of under 8 kB. It is separated into a main code and seven short functions which are easy to maintain.

The software used to program the microcontroller is an open-source integrated development environment (IDE) provided by Arduino. It is a helpful tool that contains a compiler and tools to transfer the binary files to the microcontroller. The programming language is a high-level language similar to C or C++. It is well documented, maintained and easy to learn. A lot of programs, libraries and functions can be found, which simplifies the development of a custom program. The control program for the demonstrator also uses third-party libraries and code snippets.

GEOMETRICAL AND ELECTRICAL CHARACTERIZATION

After the manufacturing of the demonstrator measurements of the width and cross-section of the printed structures were performed as well as measurements of the line conductivity.

Geometrical Properties

For the measurement of line width and cross-section a confocal laser scanning microscope was used. A plane of 532 µm by 118 µm was laid across the printed line. Then the area was scanned by the confocal laser with a 1 µm step size. At each point the height of the structure is measured. The result is a cloud of points that can be transformed into a 3D image of the surface. This measurement was performed at ten different spots showing line widths from 314 µm up to 332 µm and heights between 19 µm and 26 µm. A 3D picture of a small segment of a printed line as well as the line's cross section can be seen in Figure 7.

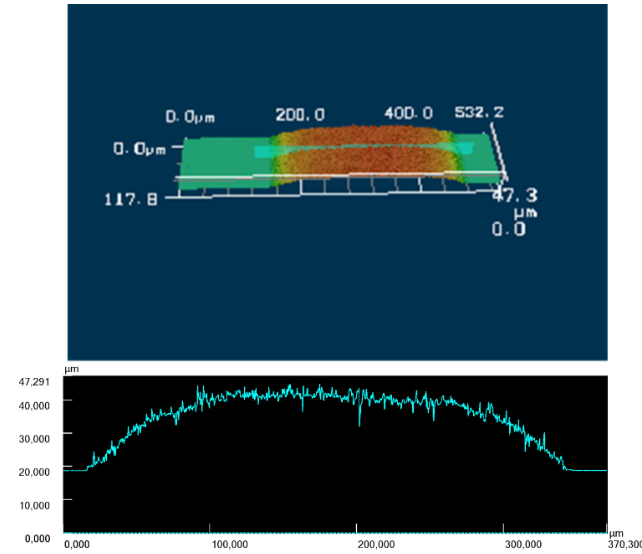

Figure 7. 3D picture of line and cross-section

With a known line width, the material reduction due to the crosshair design can be calculated. The area of a solid sensor electrode would be roughly 700 mm², whereas the crosshair design only has an area of roughly 100 mm². Thus a solid electrode would need roughly seven times the amount of silver ink used for the chosen crosshair design.

Electrical Properties

For the electrical characterization a four-point measurement of the printed lines is carried out above a distance of 3 mm at ten randomly chosen points. The measured resistance varies between 147 mΩ and 158 mΩ. Taking in account the measured line geometries, the calculated conductivity is roughly $2.2 \cdot 10^6$ S/m. This corresponds with the values given by the supplier of the paste.

CONCLUSION

In this paper the authors described the production of a low cost capacitive sensor system within a five axis CNC machine. The system was designed as a basic concept. The needed components are easy to obtain, the manufacturing is almost fully automated and the software is open source.

Main issues were the connection of the LED strip as well as the connection of the power source. The latter could be solved by developing a frame with integrated spring probe pins. The connection of the RGB LEDs has to be simplified. Replacing the RGB LEDs by either LEDs with an upside down mounting option or by a completely different indication system should be considered in future works.

Another way to improve the manufacturing process would be the installation of a curing system in form of a ultraviolet (UV) or near infrared (NIR) curing system [10]. Thus the manual process of transferring the assembled glass plate into the convection oven could be replaced and a fully functional demonstrator could be produced in a single machine.

Despite some challenges during the production, the demonstrator shows proper functionality and high reliability. The sensor is intuitive and ergonomic to operate. It detects the touch of a finger as well as the approach of a dielectric rod. Therefore, the system can also be used while wearing gloves or by people with a prosthesis. Moreover, the system is perfectly protected against environmental influences, since it is situated behind the glass. Various applications of such a sensor system are conceivable.

FUTURE WORK

The described demonstrator was developed within the scope of a research project. The aim of the project is the production of integrated mechatronic devices with communication capabilities for aerospace applications in a single machine.

As already mentioned the demonstrator was manufactured without using all advantages the five axis CNC system could provide. Therefore, next step is to use the five axis capabilities and print a sensor system on a 3D-surface like a curved airplane cabin lining element. The impact of different geometries and materials on the sensor characteristics and the performance have to be investigated. Also the characterization of the sensor electrode has to be performed. Moreover, in addition to sensors, also antennas have to be produced to establish communication between different systems and reach the goal of the research project.

ACKNOWLEDGEMENTS

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