# A flexible microrobotic platform for handling microscale specimens of fibrous materials for microscopic studies

P. SAKETI*, M. VON ESSEN*, M. MIKCZINSKI†,
S. HEINEMANN‡, S. FATIKOW† & P. KALLIO*

*Micro- and Nanosystems Research Group, Department of Automation Science and Engineering, Tampere University of Technology, Tampere, Finland

†Technology Cluster Automated Nanohandling, TC ANH, OFFIS Institute for Information Technology, Oldenburg, Germany

‡VTT Technical Research Centre of Finland, Espoo, Finland

**Key words.** Fibrous material, microrobotic, microscale samples, microscopy, sample handling, specimen handling.

## Summary

One of the most challenging issues faced in handling specimens for microscopy, is avoiding artefacts and structural changes in the samples caused by human errors. In addition, specimen handling is a laborious and time-consuming task and requires skilful and experienced personnel. This paper introduces a flexible microrobotic platform for the handling of microscale specimens of fibrous materials for various microscopic studies such as scanning electron microscopy and nanotomography. The platform is capable of handling various fibres with diameters ranging from 10 to 1000 $\mu$m and lengths of 100 $\mu$m–15 mm, and mounting them on different types of specimen holders without damaging them. This tele-operated microrobotic platform minimizes human interaction with the samples, which is one of the main sources contributory to introducing artefacts into the specimens. The platform also grants a higher throughput and an improved success rate of specimen handling, when compared to the manual processes. The operator does not need extensive experience of microscale manipulation and only a short training period is sufficient to operate the platform. The requirement of easy configurability for various samples and sample holders is typical in the research and development of materials in this field. Therefore, one of the main criteria for the design of the microrobotic platform was the ability to adapt the platform to different specimen handling methods required for microscopic studies. To demonstrate this, three experiments are carried out using the microrobotic platform. In the first experiment, individual paper fibres are mounted successfully on scanning electron microscopy specimen holders for the *in situ* scanning electron microscopy diagonal compression test of paper fibres. The performance of the microrobotic platform is compared with a skilled laboratory worker performing the same experiment. In the second experiment, a strand of human hair and an individual paper fibre bond are mounted on a specimen holder for nanotomography studies. In the third experiment, individual paper fibre bonds with controlled crossing and vertical angles are made using the microrobotic platform. If an industrial application requires less flexibility but a higher speed when handling one type of sample to a specific holder, then the platform can be automated in the future.

Correspondence to: Pooya Saketi, Micro- and Nanosystems Research Group, Department of Automation Science and Engineering, Tampere University of Technology, P.O. Box 692, FIN-33101 Tampere, Finland. Tel: +358-401981161; Mobile: +358-404188863; fax: +358-4219-198-1189; e-mail: pooya.saketi@tut.fi

## Introduction

Specimen preparation is a key step in any type of microscopy studies. However, according to Hammond and Evennett (2005), it is a laborious and time-consuming task and requires skilful and experienced personnel. They categorize specimen preparation techniques based on the sample type (biological and nonbiological), and based on the mounting type (temporary or permanent; Hammond & Evennett, 2005). Biological and nonbiological fibrous materials are of interest in such fields as composites, textiles, unwoven materials, pulp and paper and optics. In the specimen preparation processes of microscale fibrous materials, handling the specimen between the different phases in the process without introducing artefacts and structural changes to the specimen is a challenging issue. The structural changes formed while handling the specimens are mainly caused by human error. Robotic systems can reduce this damage whereas simultaneously increasing the handling throughput. At

macroscale, robotic gripping techniques have been reviewed for use with fibrous material sheets (Monkman, 1995). At microscale, the issue is harder to tackle because of the aspect ratio of fibrous materials, which may be tens of micrometres in diameter and only a few millimetres in length. Although micro- and nanorobotic technologies have been extensively utilized to handle micro- and nanoscale samples as living cells (Arai *et al.*, 2002; Georgiev *et al.*, 2004; Park *et al.*, 2004; Sun *et al.*, 2004; Inoue *et al.*, 2005; Kallio & Kuncova, 2006), optical fibres (Chen & Lin., 2004; Chen *et al.*, 2005; Ling & Lian, 2010) and carbon nanotubes (Andersen *et al.*, 2007; Carlson *et al.*, 2007), and also for promoting microassembly approaches (Ralis *et al.*, 2000; Probst *et al.*, 2009a, b; Tamadazte *et al.*, 2009) their use in microscale specimen handling is rarely reported. Examples of using microrobotics for handling biological [e.g. single cells in aqueous media (Jager *et al.*, 2000)] and nonbiological [e.g. individual tobermorite crystals for Atomic Force Microscopy studies (Yang *et al.*, 2007)] samples exist; however, microrobotic systems for the specimen handling of microscale fibrous materials have not been reported.

In this paper, we introduce a flexible tele-operated microrobotic platform to respond to the challenges of specimen handling in microscale fibrous materials. Besides increasing the throughput of sample preparation process, the microrobotic platform minimizes human interaction with the specimen and, therefore, minimizes the possible introduction of artefacts into the specimen. Other beneficial features of this microrobotics platform are the ability to manipulate a wide range of sample dimensions from 10 to 1000 $\mu$m in diameter and lengths of 100 $\mu$m–15 mm both in dry and wet states, and also the modularity of the platform. The modular features allow a promptly adaptable reconfiguration of the platform to match the needs of various specimen handling techniques for microscale fibrous materials.

## Design and implementation

### *Functional requirements*

Because microscale fibrous samples (MFSs) cover a wide range of dimensions, the platform should be able to handle fibres with diameters ranging from 10 to 1000 $\mu$m and lengths of a few millimetres. Another important factor is the ambient conditions of the sample. As many MFSs are suspended in an aqueous medium (e.g. pulp fibres in water), the platform should be able to handle specimens in both wet and dry conditions. Furthermore, in their initial state, MFSs are not organized and have a random orientation, so the platform requires an alignment process to orient the samples. Other steps in the handling process are to separate, pick, sort and mount the MFSs on specimen holders.

In many sample preparation cases, it is also necessary to treat the sample chemically by adding a known volume of different chemicals such as fluorescent labels. The platform should be able to chemically treat the fibres individually and depending on the dimensions of the MFS, the platform should be able to generate known volumes of chemicals in the nanolitre/microlitre scale, and dispense the droplet accurately on the desired place. The high aspect ratio of MFSs requires the handling of samples in three dimensions. Therefore, the platform should be capable of operating not only in two-dimensional but also in three-dimensional space. As different microscopy tools have different types of specimen holders, the platform should be modular and be able to mount the MFS on different types of specimen holders. Because specimen handling of MFS is a laborious and time-consuming task, the platform should be designed so that it can be automated in applications where high throughput is essential.

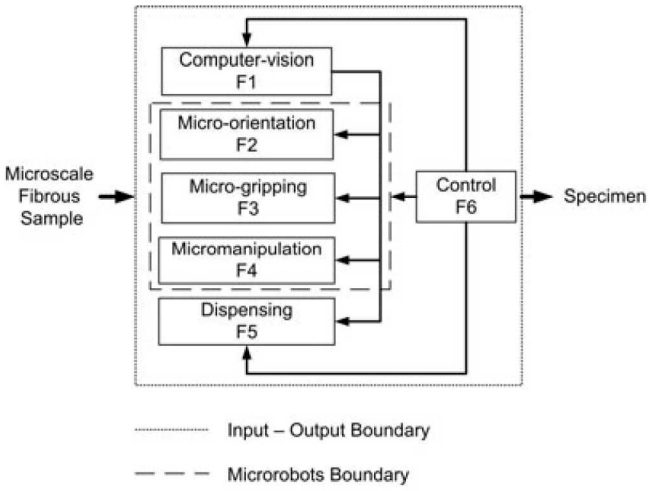



Fig. 1. Main functions of the platform.

### *Design and implementation*

The architecture of the platform is shown in Figure 1. To fulfill the aforementioned tasks, the following functions are required: the computer-vision function (F1) identifies the MFS; the microorientation function (F2) aligns the MFS; the microgripping function (F3) grasps the MFS and the micromanipulation function (F4) handles and mounts the MFS on a specimen holder. When necessary, a dispensing function (F5) treats the individual MFS chemically. The control function (F6) orchestrates the other functions and provides a user-interface for the operator.

Figures 2 and 3 show the design of the platform and Figure 4 shows the implementation of the platform. The same numbering method is used in Figure 2 and Figure 4. The stacked gantry crane structure provides several benefits such as having the most compact design without coordinate mapping and with fixed cameras. This structure holds three micromanipulators (Items 1, 2 and 3 in Fig. 2) and an *XY*-table (Item 6 in Fig. 2). The micromanipulators are composed

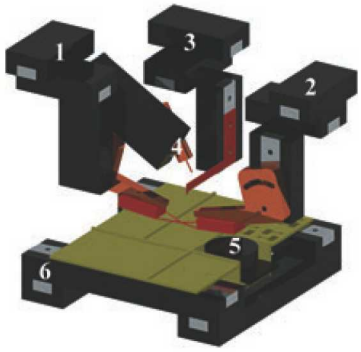



**Fig. 2.** The design of the microrobotic platform (numbering is as in Fig. 4a). (1 and 2) *XYZ* micromanipulators with active microgrippers; (3) *XYZ* micromanipulator with a passive probe; (4) dispenser; (5) microrotary-table and (6) *XY*-table.

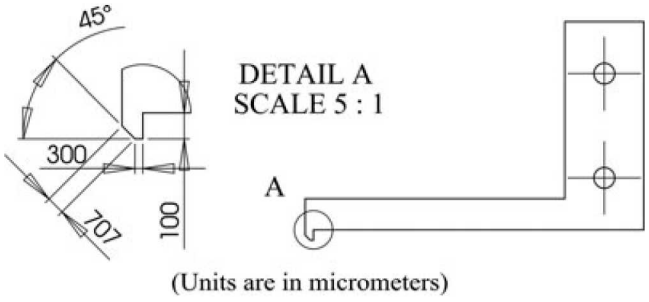



**Fig. 3.** The design of the self-fabricated mounting probe and its tip.

of three equal micropositioners (SmarAct GmbH, Oldenburg, Germany), which provide a 100-nm resolution, a $\pm 10$-$\mu$m absolute accuracy, a $\pm 1$-$\mu$m repeatability and a 21-mm travel in $X$, $Y$ and $Z$ directions. Two micromanipulators (Items 1 and 2 in Fig. 2) are equipped with active microgrippers, and the third manipulator (Item 3 in Fig. 2) is equipped with a passive probe. A linear micropositioner is added to one of the micromanipulators with an active microgripper (Item 1 in Fig. 2) to move a dispenser (Item 4 in Fig. 2) which is used for the chemical treatment of the samples. The micropositioner facilitates the application of droplets down to 70 nL with the dispenser (The Lee Co., Los Angeles, CA, USA) on any chosen location. A microrotary-table (Item 5 in Fig. 2) with a resolution of 10 $\mu^\circ$ is mounted on the *XY*-table for orienting and aligning the samples. A holder for the samples and a holder for the finished specimen are integrated onto the top of a microrotary-table. The sample holder is a small container which holds the samples either in a dry or a wet state. The specimen holder is an SEM stub, or a scanning tunneling microscopy (STM) probe which is used as a specimen holder in nanotomography (NT).

The microgrippers attached to micromanipulators (Items 1 and 2 in Fig. 2) are tailored for that purpose and have exchangeable jaws with an opening gap of 1 mm (SmarAct GmbH). The passive probe attached to the third micromanipulator (Item 3 in Fig. 2) is a stainless-steel probe

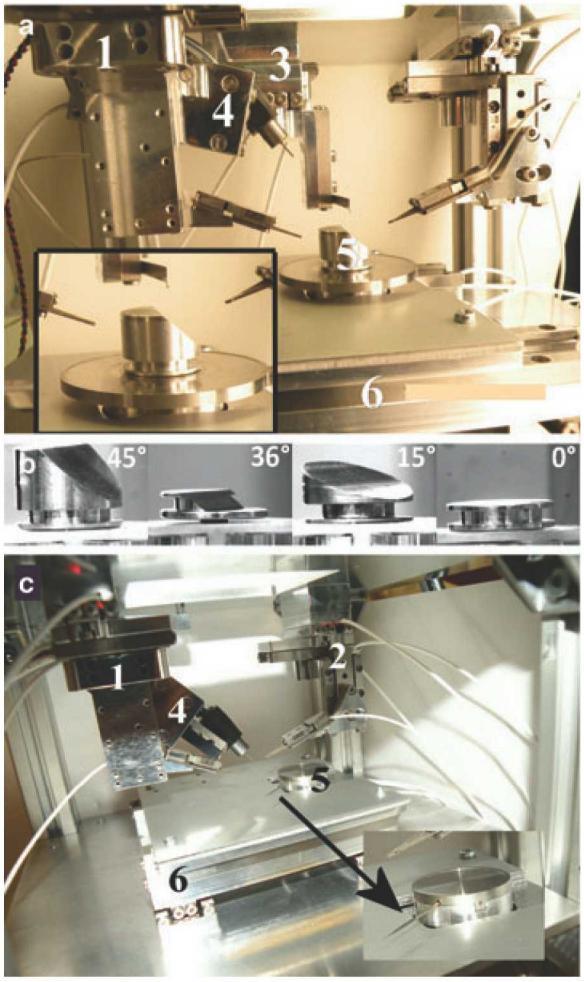



**Fig. 4.** The configuration of the platform (numbering is as in Fig. 2). (a) The platform configuration for the specimen handling of MFS for SEM imaging. (b) Stubs with varying inclination: 0°, 15°, 36° and 45°, all with a diameter of 12.5 mm. (c) The platform configuration for the specimen handling of MFS for NT imaging.

fabricated using laser-micromachining. Figure 3 shows the design of the mounting probe. The tip of the probe is designed in such a way that it allows the mounting of MFS on both horizontal and inclined specimen holders. The 300-$\mu$m horizontal edge on the tip is used for mounting the MFS on horizontal specimen holders, and the inclined 707 $\mu$m edge with the 45° angle is used for mounting on inclined specimen holders.

All micropositioners (with the exception of the dispenser micropositioner) are equipped with position sensors. The dispenser micropositioner and the microrotary-table are controlled using visual feedback. A 12 × computer-controlled zoom with 0.29–3.5 × magnification, a fine focus and an illumination system (Navitar Inc., Rochester, NY, USA) and a CCD camera (SONY XCD-U100) provide visual feedback from the top. A 6× macro–zoom-lens (Optem, Munich, Germany) and CCD camera (SONY XCD-X710) provide the side view.

The pixel sizes of the top-view and side-view cameras are 4.4 and 4.65 $\mu$m, respectively.

Figure 4 shows the configuration and the modular features of the microrobotic platform; numbering is as in Figure 2. The modularity of the platform eases the configuration of various samples and sample holders. The first configuration of the platform (Fig. 4a) is designed to handle specimens of MFSs for SEM imaging. The sample container is a stainless steel dish with a depth of 100 $\mu$m. This depth guarantees that the fibres cannot stay inclined in the medium and that they are graspable with the microgrippers. In this configuration, the specimen holder is an SEM stub in the centre of the microrotary-table which is available in various inclination angles and can be easily changed depending on the imaging needs (Fig. 4b). The second configuration of the platform is designed to handle specimens for NT imaging (Fig. 4c). The depth of the sample container is 100 $\mu$m—the same as in the first configuration. An STM probe is used as the specimen holder for NT imaging. It is attached to the microrotary-table to align the sample with the probe.

The operator interacts with the platform using a user interface, which is provided by the control software (CS). In addition to the user-interface, the main responsibility of the CS is to provide the functionality required to control the devices attached to the platform and also the CS is responsible for acquiring data from sensors and cameras attached to the platform. In a typical scenario, the operator uses the CS as follows: the operator places the MFS in the sample container and visually inspects the fibres via the provided user-interface. The operator is responsible for selecting the best MFS. In the next phase, the operator aligns the selected MFS with microgrippers using the microrotary-table and moves the microgrippers to the proximity of the end points of the MFS. The selected fibre is grasped by closing both gripper jaws synchronously. After the fibre is successfully grasped, it is moved onto the specimen holder and aligned appropriately. Finally, the fibre is mounted on the specimen holder using the passive probe. Figure 5 illustrates the signal flow diagram in CS during the tele-operated specimen handling processes.

## Materials and methods

This section explains the experiments performed with the platform. The first experiment prepares the specimens for a diagonal compression test of paper fibres inside an SEM. In this experiment, the individual paper fibres are mounted on SEM specimen holders using the two microgrippers and the passive probe. The performance of the microrobotic platform is compared with a skilled laboratory worker performing the same experiment. The second experiment includes mounting a strand of human hair and a paper fibre bond for an NT investigation on STM probes by using one microgripper. In the third experiment, two microgrippers and the dispenser are used for creating individual paper fibre bonds.

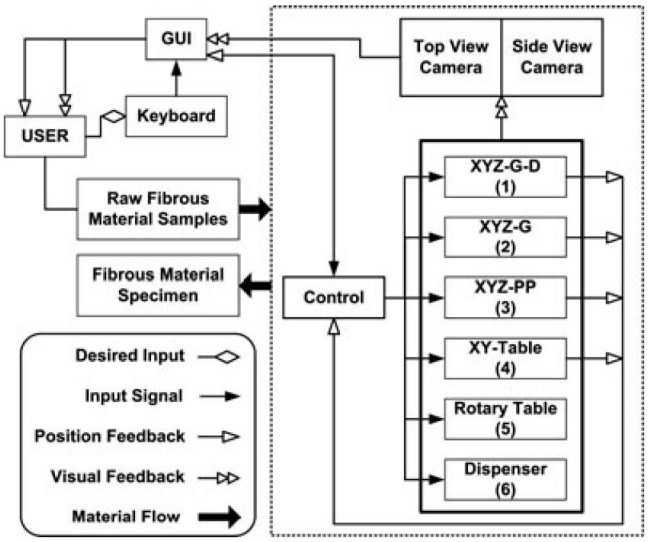



**Fig. 5.** Signal flow diagram during the specimen handling processes. *XYZ*: The 3DOF micromanipulator; G: including microgripper; D: including Dispenser positioner; PP: including Passive Probe.

### *Specimen preparation for a diagonal compression test inside an SEM*

To image small specimens with a scanning electron microscope, the specimens are generally placed on carriers referred to as stubs. These carriers are available in different sizes and materials, such as aluminum or copper (Agar Scientific, Essex, UK). Stubs with a diameter of 12.5 mm and a varying inclination angle [0°, 15°, 36° and 45°, (Fig. 4b)] were used for the experiments. The inclined stubs ease the approach to the fibres with microrobots inside the SEM. To mount the paper fibres on the stubs, two pieces of adhesive carbon pad are fixed onto the stub surface. Since paper fibres are natural fibres with largely varying lengths, the pads form a narrowing groove, in the shape of a "V". This "V" shape groove guarantees that fibres with different lengths can be mounted.

Figure 6 and Video 1 illustrate the process of specimen preparation for a diagonal compression test of a paper fibre inside an SEM. The MFSs in this experiment are pine paper fibres which are disintegrated in deionised water and placed on the microrotary-table by using a pipette. To mount the both ends of a fibre on the edges of the "V" shape groove, two microgrippers grasp an individual paper fibre at both ends and lift it above the microrotary-table to a suitable height so that the stub can move under it (Figs. 6a and b). Then, the paper fibre is aligned with the "V" shape groove to match its length. The alignment process is a combination of fine movements with the microrotary-table and the *XY*-table (Fig. 6c). To increase the accuracy of mounting, the mounting probe pushes one end of the grasped fibre—very close to the microgripper—to the carbon pad while holding the both ends of the fibre with the microgrippers (Fig. 6d). The same process is repeated for mounting the other end of the fibre onto the

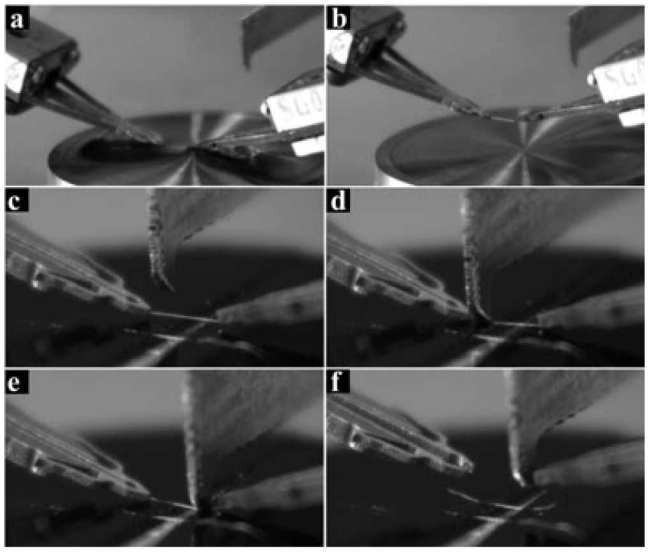
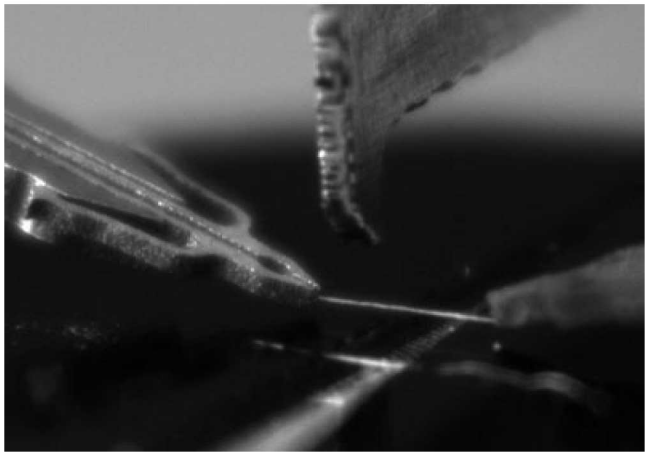



**Fig. 6.** The process of paper fibre specimen preparation for the diagonal compression test inside an SEM. (a) and (b) Two microgrippers grasp an individual paper fibre at both ends and lift it above the microrotary-table to a suitable height so that the stub can move under it; (c) The paper fibre is aligned with the "V" shape groove of the carbon pad to match its length; (d) and (e) The mounting probe pushes one end of the grasped fibre at a time—very close to the microgripper—to the carbon pad while holding the both ends of the fibre with the microgrippers and (f) The microgrippers release the fibre ends after the mounting process is over.



**Video 1.** The process of paper fibre specimen preparation for the diagonal compression test inside an SEM (Video-still image).

carbon pad (Fig. 6e). Finally, the microgrippers release the fibre ends after the mounting process is over (Fig. 6f). The process is repeated for mounting several fibres on differently inclined stubs. The paper fibres ranged from 25 to 34 $\mu$m in diameter and 0.8–3 mm in length.

The paper fibre diagonal compression tests were carried out in a Tescan Lyra 3 XHM scanning electron microscope. After mounting the stub on a fine positioning unit (Physik Instrumente, Karlsruhe, Germany), a microforce sensor

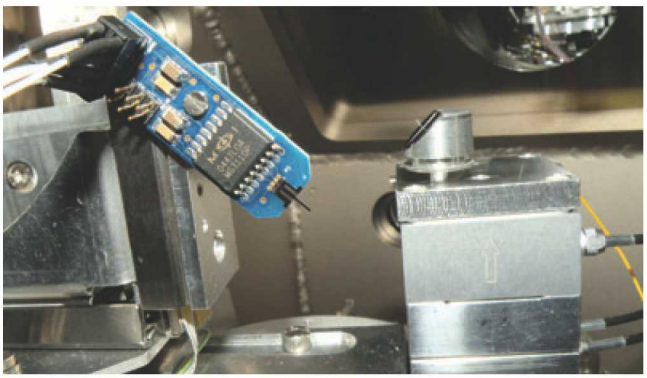


**Fig. 7.** On the left, the coarse positioning unit with the microforce sensor. On the right, the fine positioning unit with a stub. Here, a 45°-angled stub was used to ensure observation with the SEM (from top).

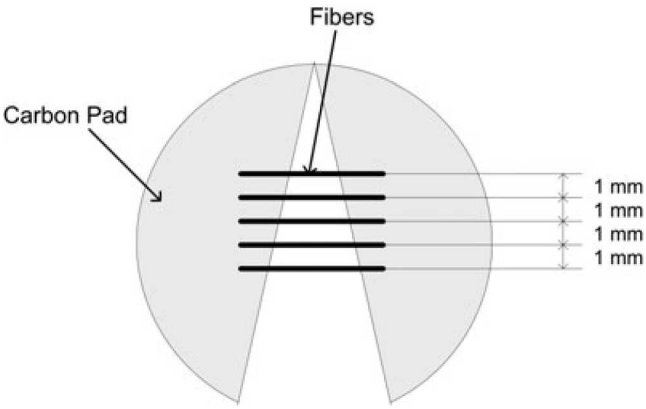



**Fig. 8.** Schematic of reference paper fiber mounting task to compare the skilled worker accuracy and speed with the microrobotic platform quantitatively.

(Femtotools, Zurich, Switzerland) mounted on a coarse positioning unit (SmarAct GMBH) was directed close to the fibre. The sensor with a square flat tip of 50 $\mu$m × 50 $\mu$m pressed the fibres against the stub surface, which acted as the rigid reference surface. This movement was performed by the fine positioning unit. Figure 7 shows the setup in an overview image. The diagonal compression tests were carried out on individual paper fibres to measure the collapsibility of the lumen of paper fibres, which affects the compactibility of paper hand sheets on an industrial level.

To compare the precision and speed of mounting the fibres using the microrobotic platform with manual work of a skilled worker quantitatively, the following task was defined and performed: five fibres were mounted on a stub with the distance of 1 mm from each other as illustrated in Figure 8, and it was repeated four times.

The process of mounting paper fibres on SEM stubs using microrobotic platform was already mentioned in the beginning of this section (Fig. 6). The consumed time to perform the assigned task using the microrobotic platform

was calculated from the time stamps of the sequence of images recorded during the process. The average time to picking up an individual paper fibre from the diluted pulp suspension was 67 s per fibre (Figs. 6a and b). The main challenge in picking up the suspended individual paper fibres from water was the shadows cause by water meniscus around the microgripper jaws; Figure 6(a) illustrates this problem. These shadows complicate the detection of paper fibre endpoints in the top view when the microgrippers are inside water.

The average time to perform the fibre alignment and position the fibres in the requested distances from each other needs the average time of about 28 s per fibre (Fig. 6c). The required time to mount the both ends of a fibre, open the microgrippers and lift them was 75 s (Fig. 6d–F). Therefore, the average time for the entire process was 170 s per fibre. The total required time to perform the assigned task of mounting five fibres on each stub using the microrobotic platform was about 14 min per stub.

A skilled laboratory worker performed the aforementioned assigned task manually to compare the results with the microrobotic approach. The manual paper fibre mounting steps are as follows: disintegrating the paper fibres; diluting a drop of concentrated fibre slurry in a Petri dish; putting a drop of water on a microscope glass slide; taking single fibres from the Petri dish which seem to be long enough using tweezers (Dumoxel nonmagnetic, size 5) and placing them into the water droplet on the glass slide by naked eyes. Then taking the first fibre with the tweezers from the glass slide and bring it to the stub; positioning the fibre to match the width of the "V" shape groove on the carbon pad and pressing one fibre end onto the carbon pad using the tip of the tweezers. Positioning the other fibre end using a stereo microscope and mounting it using the tweezers. Repeating the same process for the next four fibres.

The most time-consuming part of the process was to separate the individual paper fibres from disintegrated fibres; grasping and mounting them on the stub was less time consuming after the training. Excluding the required time to separate the individual fibres from the disintegrated fibres, the learning curve showed that preparing the first stub took about 20 min but the time was reduced to approximately 7 min for the last stub. The entire process of mounting 20 fibres on four stubs (five fibres per stub) took approximately 80 min. The total required time to perform the assigned task of mounting five fibres on each stub manually was about 20 min per stub.

*Specimen preparation for NT*

In the NT studies, an STM tungsten probe was used as the sample holder for a strand of human hair and also for an individual paper fibre bond. Figure 9 shows the process of handling a strand of human hair with a diameter of 142 $\mu$m for NT. The microgripper grasped the human hair in a dry state from the microrotary-table and aligned it both

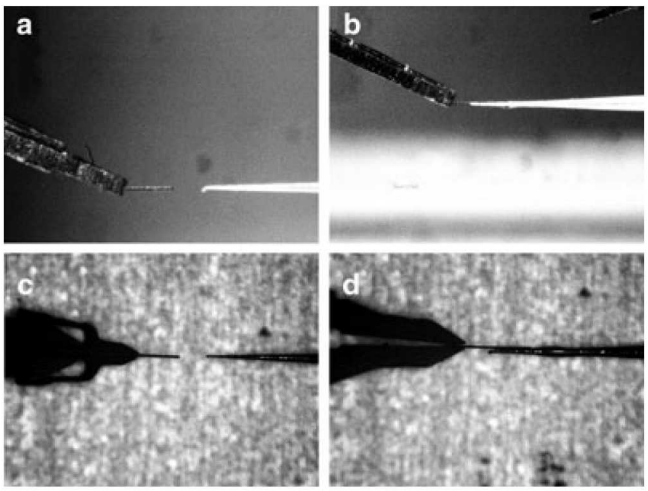



**Fig. 9.** The process of handling human hair for NT studies. (a) and (b) side view; (c) and (d) top view. The diameter of the hair sample is 142 $\mu$m.

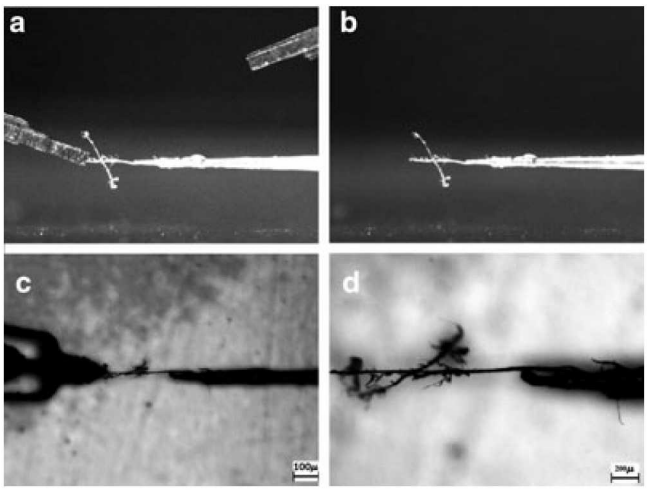



**Fig. 10.** The process of specimen handling for NT studies of individual paper fibre bonds. (a) and (b) side view. (c) and (d) top view.

vertically and horizontally with the STM probe (Figs. 9a and c). The coordinates of the microrotary-table are saved. The microrotary-table turned the STM probe, dipped it in glue and returned it back to the saved coordinates. Finally, the microgripper moved the hair fibre close to the STM probe for mounting (Figs. 9b and d).

Individual paper fibre bonds are delicate samples to manipulate—they require approximately 1–10 mN to break—and they exhibit a more complex shape than single fibres. Figure 10 shows the process of the specimen handling of an individual paper fibre bond for NT. The process steps are similar to the handling of the human hair.

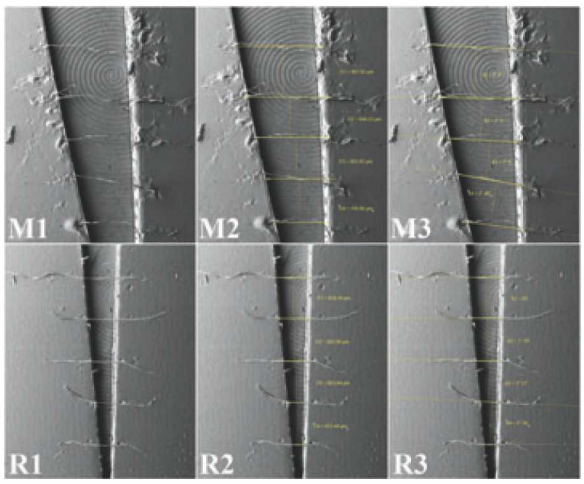



**Fig. 11.** Representative images comparing the results of mounting of paper fibres manually with the results of mounting of paper fibres using microrobotic platform.

*Making individual paper fibre bonds*

The crossing angle and the vertical angle are two important parameters in determining the bonded area between two paper fibres. The crossing angle directly affects the bonded area between the two fibres. The vertical angle is the angle between the fibre bond plane and the image plane (Kappel *et al.*, 2009). In an earlier reported method of making individual paper fibre bonds, a highly dilute suspension of fibres was prepared and the droplets of the suspension were placed between two Teflon plates and dried for 45 min (Kappel *et al.*, 2009). The randomly oriented paper fibres in this method lead to both random crossing and vertical angles; however, the desired crossing and vertical angles are 90° and 0°, respectively. To make individual paper fibre bonds with the desired angles, an active microgripper was replaced with a passive probe. In making the bond, two perpendicular microgrippers grasped individual paper fibres and crossed them on each other on a Teflon plate. The Teflon plate was placed on top of the *XY*-table. The dispenser applied a 70-nL droplet of water onto the fibre intersection. The water was used for creating a hydrogen bonding between the two paper fibres. Another Teflon plate was used to cover the first and to press the fibres together. Finally, the Teflon plates were placed in an oven (Binder GMBH, Tuttlingen, Germany) for 45 min under 140 kN $m^{-2}$ pressure and 70°C temperature. The details of the configuration of the platform and the bond making process using microrobotics are reported (Saketi & Kallio, 2011).

## Results

Figure 11 shows the representative SEM images of individual paper fibres mounted on the stubs. The images in the top row of Figure 11 show the individual paper fibres mounted manually (Fig. 11-M1–M3), and the images in the bottom row show the individual paper fibres mounted using the microrobotic platform (Fig. 11-R1–R3). The following four parameters are taken into account to compare the results of the manual approach with the microrobotic approach: time, gap between the fibres (Fig. 11-M2 and R2), angle between the fibres (Fig. 11-M3 and R3) and curliness of the fibres. Table 1 briefly compares the results of manual approach with the microrobotic approach and presents the aforementioned parameters quantitatively. Preparing the paper fibre specimens using the microrobotic platform consumes 30% less time than the manual approach, improves the mounting precision and reduces the fibre curliness. Even though the average gap of $670.0 \pm 10.9$ $\mu$m between the fibres indicates that the microrobotic platform provides better mounting precision compared to the manual approach ($824.3 \pm 150.3$ $\mu$m), but it also indicates that there is 330 $\mu$m offset from the target gap of 1 mm. This offset can be compensated by calibrating the platform in the future. Besides the aforementioned achievements, another major achievement in this specimen preparation process is to avoid the introduction of any artefacts to the paper fibre samples. Only the end points of the fibre were affected by the microgrippers and the central parts were totally untouched.

**Table 1.** Comparing the results of manual approach with the microrobotic approach.

| | Manual approach | Microrobotic approach |
|---|---|---|
| Average time per stub (min) | 20 | 14 |
| Average gap between the fibres ($\mu$m) | $824.3 \pm 150.3$ | $670.0 \pm 10.9$ |
| Average angle between the fibres (°) | $5.1 \pm 3.1$ | $1.4 \pm 0.8$ |
| Average curliness of the fibres ($\mu$m) | $90.7 \pm 28.1$ | $30.1 \pm 3.1$ |

The human hair and the paper fibre bond were mounted on the STM probe successfully. The inspection of paper fibre bonds using NT provides important information about their bonding mechanism, illustrates the interaction between the two fibres in the bonded area and measures the real bonded area. The making of individual fibre bonds was demonstrated successfully (Saketi & Kallio, 2011) and the use of the platform can minimize the artefacts of the conventional bond making process. As the individual paper fibre bonds are made using the microrobotic platform, the bonds have the desirable crossing angle, close to 90°, and also the desirable vertical angle, close to zero (no random angles).

## Conclusion

A modular microrobotic platform for the handling of microscale fibrous specimens for microscopy applications was designed and developed. In the experiments, paper fibre and human hair have been used as representative MFSs. Three types of specimen handling processes have been performed to demonstrate the capabilities of the platform. In a specimen handling process for the diagonal compression test of paper fibres inside an SEM, the paper fibres were successfully mounted on the stubs with high precision and minimum human interaction. Comparison of the manual approach and the microrobotic approach indicates that the specimen preparation time was reduced by 30%. The coefficient of variance for the gaps between the fibres with the manual approach was 18.2% and with the microrobotic approach was 1.6% which indicates that the microrobotic approach is much more precise than the manual approach. In handling specimens for NT, the mounting of a strand of human hair and an individual paper fibre bond on a specimen holder (an STM probe) was successfully demonstrated using the microrobotic platform. Taking into account the small force which bonds two individual paper fibres together, mounting an individual paper fibre bond on the sample holder without damaging it was a distinctive achievement. In the conventional methods of making individual paper fibre bonds, the fibres are randomly oriented which leads to random crossing and vertical angles. Creating individual paper fibre bonds using the microrobotic platform, results in desirable crossing and vertical angles. Controlling the quality of the specimens of individual paper fibre bonds in both the making and the mounting phases, can help paper fibre scientists to achieve better results in their experiments. From this, a better understanding and analysis of the true nature of bonding mechanisms between two paper fibres can be reached, than was previously possible. Considering all the aforementioned specimen handling processes, this level of accuracy on manipulating and mounting the microscale fibres is out-of-reach in manual specimen handling processes.

The experiments performed demonstrate that using the platform makes it possible to prepare specimens from various fibrous materials without the introduction of artefacts. The samples can be placed on various holders to be used in a wide range of microscopy applications. It is also possible to treat the samples with different chemicals before microscopy is undertaken. Using the platform does not need extensive experience on microscale manipulation and a short training period is sufficient for the operator. The requirement of flexibility and easy configurability for various MFSs and specimen holders is typical in material research. To facilitate flexibility, the specimen preparation processes described in this paper are performed in a tele-operation mode. However, if a future industrial application requires less flexibility but higher speed, the platform provides an infrastructure to prepare stacks of microscale fibrous specimens automatically. Even though only paper fibre and human hair have been used in the experiments, the capabilities of the platform support the handling of other fibrous materials such as glass fibres in the same dimensional range.


## Acknowledgements

The authors thank the Finnish Funding Agency for Technology and Innovation (TEKES) for funding this project; Malte Bartenwerfer from Division Microrobotics and Control Engineering (AMiR) at University of Oldenburg, Germany, for his support; Raphael Passas at ING-Pagora-Grenoble for his comments on the fibre compression measurements and Markko Myllys from Department of Physics, University of Jyväskylä, Finland for providing the NT specimen holder and images.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