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Development of a membrane-shaped MR-based composite draping tool

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Abstract

Nowadays, the manufacturing process of composite parts is still dominated by a high level of cost-intensive manual tasks which impedes the use of these materials in composite processing SMEs as well as in high-end automotive and aerospace industries. The draping of fibre sheets is often still carried out manually because of the difficult handling properties, the high variety and complexity of the materials and the product contours. Even the current manipulation tools, for composite draping or preforming in moulds, often lack controllability and flexibility to cope with a high mix of features in the composite product. In automation, these problems are often answered by cost-increasing multi-robotic systems, using multiple degrees of freedom in combination with a large range of feature-specific tools. The need for rather simple, cost-effective manipulation tools triggered the development of a membrane-shaped magnetorheological (MR) based composite draping tool. First, a fluid-filled bag will cover the mould entirely and will perform the initial forming of the composite material whilst both preventing the creation of wrinkles and securing the readily draped areas during further processing. Subsequently, by applying local pressure on the fibre sheet through magnetic activation, draping in narrow or corner-like features will be enhanced. Furthermore, slippage of fibrous material between the membrane and the mould surface can be mastered during forming, facilitating the control of fibre orientation and shear angles. First experimental tests indicate that this technique shows large potential to enable full automation of the entire draping process by the flexible use of a single robot arm and multitool whilst being product and feature independent.

Keywords:
Preforming ; Dry fibre sheets ; Composite ; Draping

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1. Introduction

Due to their high strength-to-weight ratio, high chemical resistance, design flexibility and durability, composites have become more often the material of choice for a growing range of applications within the aerospace, automotive and a multitude of other sectors. However, there is still a threshold for small and medium-sized enterprises (SMEs) to implement composite solutions in their sector. Cost-effective production remains a challenging factor in these flexible high-mix, low-volume production scenarios, mainly caused by highly labour intensive handling and draping of fibrous material in liquid composite moulding (LCM) processes such as vacuum assisted resin infusion (VARI) and light resin transfer moulding (RTM light) [6].

This paper is organised as follows. First, Section 1 provides a short introduction about the composite part production industries' current state. This is followed by a review of state-of-the-art systems for handling dry fibrous materials in Section 2, focusing on their specific advantages and disadvantages. The shortcomings of these tools in combination with the overall process constraints, comprise the system requirements for the developed tools discussed in Section 3.1. Section 3.2 describes the iteration steps in the design process of the draping tool for dry fibre sheets and in Section 3.3, the delivered work on composing a suitable deformation material, in particular MR fluid, is studied in more detail. Section 3.4 delineates the pilot setup, made to assess the draping quality of the developed draping tools based on 3D measurement data. In Section 4, results regarding the application of the developed draping tools to various moulds in the pilot setup are communicated. Section 5 discusses the results of current research and analyses possible future research tracks. Finally, Section 6 concludes with a summary of this work.

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2. Related work

Analyses of the manual operations during contemporary lay-up, demonstrate three main tasks that should be fulfilled by one or more composite automation tools: gripping, draping and optionally fixation. Firstly, the fibre sheet needs to be taken from a supply and moved to the mould. During this process the desired fibre orientation should be considered and unwanted distortions in the fibrous material due to handling should be minimised. Secondly, the forming of the fibrous material to the desired shape in the mould can be executed in multiple steps, whether or not in contact with the mould itself. After a certain feature is formed, the fibre sheet can be fixed by a binder to prevent deformation in the subsequent steps as seen in preforming processes.

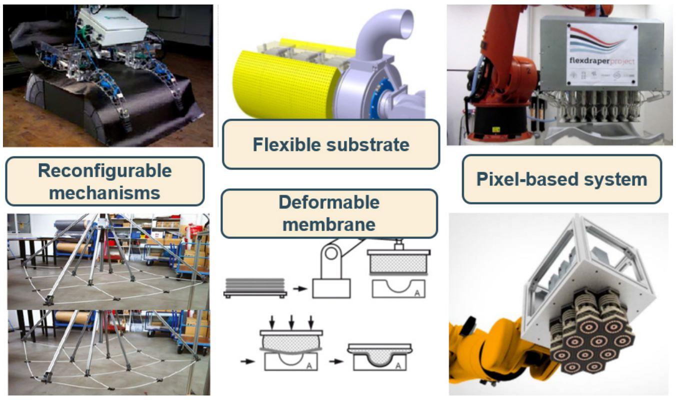

Fig. 1: Non-exhaustive overview of the four main categories in draping/preforming dry fibrous material: flexible substrate-based systems [5], pixel-based systems [7, 9], reconfigurable mechanisms [11, 8] and deformable membrane-based tools [10].

A multitude of potential solutions have already been presented regarding the draping or preforming of dry fibrous material in these production scenarios. These solutions can be divided into four main categories: (1) flexible substrate-based systems, (2) pixel-based systems, (3) reconfigurable mechanisms and (4) deformable membrane-based tools, with Figure 1 showing a non-exhaustive list of recent developments. The first category mainly consists of concave tools equipped with a flexible substrate (e.g. foam) that adapts to the mould's shape and forms the fibrous material as presented in [2]. Here, gripping is done by flexible electroadhesion pads or suction holes in the substrate's surface. The second category are tools provided with a large number of grippers serving as grid pixels (e.g. suction cups arranged in a large controllable grid) as presented in [9]. These grippers can be controlled in height to adapt to the shape of the mould. It is also possible to control the slippage between the fibres and the gripper during the forming process by selective adjustment of the gripping force as presented in [7]. The third category of tools consist of grippers mounted on a large variety of reconfigurable mechanism. These mechanisms are designed to pick flat fibre sheets from a supply and apply an initial deformation to the fibre sheet before it is placed in the mould. For example, a deformable net-based structure with suction cups on the nodes as presented in [8]. Another solution is shown by [11], where a bio-inspired octopus arm equipped with electrostatic grasping pads [3] is used to drape a large single-curved surface.

The previously mentioned three categories provide proper gripping, draping and fixation functionalities for the specific proof-of-concept moulds demonstrated. When trying to implement these systems in high-mix low-volume production scenarios of complex products most of them will meet their limits. The first category is limited in draping deep narrow features e.g. stiffener ribs. When the foam is pressed against the fibre sheets, placed in the mould, an overall draping force is exerted and starts to form the fibres into the mould's cavity (Fig. 2). While the holding force present at the cavities' edges remains stable, the draping force will decrease due to the foam's compression characteristics causing the limited mouldable maximum feature depth. For the second category, the smallest mouldable feature is limited by the grid pixel size, which is inversely proportional to the tool's complexity and cost. In addition, sharp 90 degrees walls that are not perfectly aligned with the tool's grid pixels can cause damage. The third category has limitations regarding the number of necessary degrees of freedom (DOF). For example, some draping tools as presented by [3] can only adapt to a single-curved surface, meanwhile [8] demonstrates draping in a double-curved surface but only with a limited curvature. Besides this, these systems are not able to cope with small features on large curvatures.

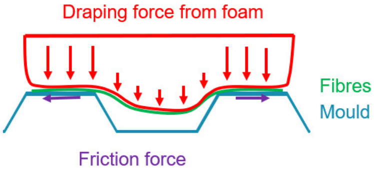

Fig. 2: Limited mouldable maximum feature depth of flexible substrate-based systems, caused by a decrease of the draping force due to the foam's compression characteristics, meanwhile the holding force present at the cavities' edges remains stable.

The fourth category of draping tools tries to give an answer to the mentioned limitations by means of a flexible membrane, filled with a deformable matter, that is able to adapt to a more versatile range of moulds. The Formhand [10] is composed of a granulate-filled membrane of which the stiffness is vacuum controlled based on the granular jamming principal [1]. Additionally, the tool generates a suction force through perforation in the grasping surface. This tool's functionality is twofold, namely grasping fibre sheets and subsequently pressing and forming it into the mould's shape. During this latter step, the entire tool together with the fibre sheets are deformed to the mould's shape, meanwhile the draping process is controlled by mastering the flowability of the granulates through vacuum.

Comparing the aforementioned systems with the manual draping process, one main action none have been able to imitate is distinguished. Namely, locally applying force in a continuous manner with a compliant tool whilst selectively fixating the remainder of the fibres in order to control shear and to ensure a satisfactory draped part. In the manual draping process this action is performed by the human operators' hands and fingers. The draping tools proposed in this paper aim to answer this shortcoming by a membrane-shaped water-based and MR-based tool to respectively enable human-robot collaboration (HRC), and to apply locally a magnetic attraction force and a tool stiffness change in order to enhance composite draping. According to [4], there is a potential for magnetorheological materials in robotic grippers, which can even be extended to manipulation tools for clamping, grasping and draping, the domain of interest of this paper.

3. Methods

3.1. System requirements

This work only focuses on one of the three essential functions (gripping, draping and fixation) that composite automation tools must perform in an automatic lay-up of fibre sheets. In the draping stage, it is recommended that the tool has a high formability to deform to the mould's shape and thereby exerting an evenly distributed force on the fibre sheets. The contact surface of the tool may not be sticky and needs to allow slippage between itself and the fibres. Due to the potential risk of silicone contamination, most composite processing companies are still sceptical about the use of silicone tools in their production processes even though for instance its use in reusable bagging material is becoming more frequent. Furthermore, the tool need to ensure the overall securing of movement of the fibre sheets while draping multiple cavities in one mould. These draping and fixation requirements describe behaviour that can be attributed to liquids. In order to have a high operational speed and a low tool cost, the liquid respectively needs to have a low viscosity to maintain the flowability and needs to be inexpensive. In the case of a leakage, ideally the contamination should be harmless to the fibre sheets. Additionally, a high mass density of the liquid will increase the overall exerted draping forces, where the benefit depends on the combination of mould, fibres, gel coatings, etc. Finally, a method of place specific force application should be integrated in the tool to drape the fibres or to fixate them in order to control deformation during draping.

3.2. Design of draping tools

The tools presented in this work focus on improving the draping step (par. 3.1) whilst still maintaining the opportunity to integrate the two other steps of gripping and fixation in the future as discussed in (par. 5). The tool consist of a fluid-filled high-density polyethylene (HDPE) bag with a thickness of 30 μm mounted on an aluminium frame (L x W: 600 x 460 mm). The membrane thickness is sufficiently thin to enhance its formability and reduce the forces needed to deform to the mould's shape. Besides this, it is thick enough to prevent the adverse effects of reduced strength and durability. The bag has a working area of 450 mm by 350 mm with two loops (L x W: 450 mm x 150 mm) welded on each side of the bag, which are slid over the aluminium frame.

In the first design iteration, the bag is filled with tap water in order to proof the concept. Here, it is found that without any local pressure on the fibre sheet the draping on a 3D surface is insufficient. Subsequently, local pressure is applied by pressing manually on the fibre sheet at the level of cavities and corners. By making the bag transparent and thereby allowing the underlying cavities to be visible, this draping tool could be used on a collaborative robot in cooperation with a human operator. Alternatively, the human operator can even be replaced by a single robot arm production cell. Here, the proposed tool fixates the draped fibre sheets while a robot whose end effector is equipped with a flexible substrate-based system (e.g. foam roller) applies local pressure. Fixation by this manner eliminates the need for a multitude of additional robots or systems. Additionally, the membrane reduces the creation of undesirable distortions or deformations by allowing easy slippage between the fibre sheets and the bag, which could for instance prevent the transfer of detrimental shear stresses to the fibres when draping with a deformable foam roller. The foam roller's deformation namely induces different rolling diameters across the roller's cross section, combining this with its constant rotation speed, shear stresses will be exerted between different parts of the roller. The main disadvantage of this full automatic approach is still the multitude of diverse tools needed to mimic the universal compliance of the human hands and fingers.

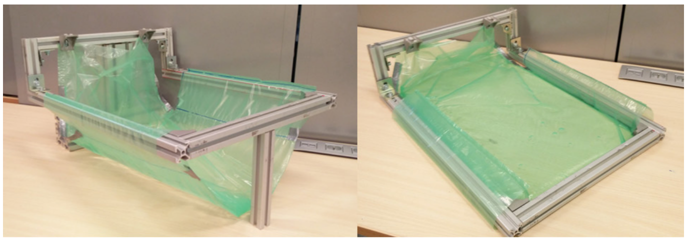

Fig. 3: Water-based tool. Left: transport position, right: draping position.

In the second design iteration, the bag is filled with a magnetorheological (MR) fluid, a composition of synthetic oil and micron-sized iron particles. Dependent on the shape of the mould, the higher mass density of this liquid relative to water ensures a better draping of the fibre sheet at the same volume, albeit still insufficient. Here, local pressure is applied by placing a magnetic field under the mould such that the fibre sheet, sandwiched between the bag filled with MR fluid and the mould, is pressed against the mould. In this work the magnetic field is provided by a neodymium N45 permanent magnet with a load capacity of 38 kg, which can be mounted on a robotic system so that fully automatic lay-up can be enabled. This approach eliminates the needs for multiple compliant tools through the almost infinite adaptability of the fluid and inherent compliance of the used force. The concept illustrations of both designs are shown in Figure 4.

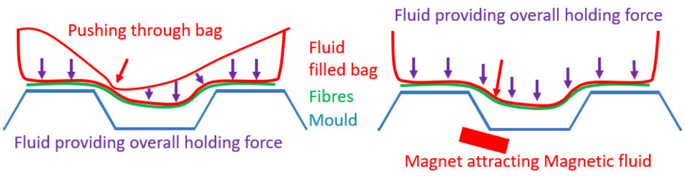

Fig. 4: Concept illustrations of the developed draping tools. Left: water-based tool, right: MR-based tool.

3.3. Composition of magnetorheological fluid

The magnetorheological (MR) fluid, applied in this work, consists of micron-sized round-shaped iron particles (CAS 7439-89-6) with a size distribution between 1 and 5 μm suspended in a carrier liquid of synthetic carter oil EP680 developed for lubricating enclosed gears operating under severe conditions, respectively obtained from Merck Inc. and Total S.A. This synthetic carter oil EP680 has a standardised kinematic viscosity of 680 mm^2/s at 40 °C and a mass density of 904 kg/m^3 at 15 °C. Finally, the bag of the draping tool has been filled with 4 litters of synthetic carter oil EP680 and 1 kg of the aforementioned iron powder, a total mass fraction of 22 m%.

3.4. Design of pilot setup

The designed draping tools were tested on a pilot setup equipped with a computer vision system and consisting of three characteristic moulds, shown in Figure 5, which are compliance with the proposed requirements (par. 3.1). The first mould is a lid (L x W x H: 680 x 460 x 45 mm) provided with three rounded reinforcement ribs with a depth of 15 mm and a mutual distance of 150 mm and made from medium-density polyethylene (MDPE). The second mould is a aluminium conical bowl with a depth of 45 mm and a top and bottom diameter of respectively 180 mm and 130 mm. The third mould is a gel-coated composite air grabber. The section of interest of this mould has a raised wall with a height of 40 mm. Finally, the draping of a generic twill-woven glass fibre sheets (L x W: 450 x 350 mm) in these moulds are inspected with a centrally mounted ENSENSO stereovision 3D camera at a height of 900 mm in combination with the GOM Inspect software to evaluate 3D measurement data. Fibre orientation and the presence of distortions are inspected visually.

4. Results

Both developed water-based and MR-based draping tools are tested on the three aforementioned moulds and deliver satisfactory results when draping a single layer of generic twill-woven glass fibre sheet, of which 3D measurement data is shown in Figure 6. The point clouds of the moulds and fibre sheets are superimposed, so that absolute height differences between 0.2 and 1.0 mm, respectively the approximate dry fibre thickness and this thickness extended with a small amount of springback, can be assumed to be perfectly draped areas. Due to filtering and smoothing steps performed to alleviate the negative effects of reflections by the glass fibres and the camera accuracy, these absolute height differences should be interpreted with caution. It is therefore recommended to focus on relative height differences between local areas instead of absolute values. Overall performance regarding fibre orientation and distortion are inspected visually, with no systematic irregularities being observed. Although, the implementation of a thoughtful draping strategy or sequence is not neglectable when using these tools. Finally, some mould and tool specific remarks are made in this section.

Fig. 5: Three characteristic test moulds. Left: MDPE lid with reinforcement ribs, middle: aluminium conical bowl, right: composite air grabber.

4.1. Lid mould

The areas at the centre of the mould, indicating significant absolute height differences, are outside the operating range of the tools and should therefore be excluded from the results. Both tools perform well with regard to the draping quality, especially the MR-based tool provides better results at both the bottom corners of the reinforcement ribs and the double-curved outer corners of the mould. Only the upper left corner of the mould was not properly draped by the MR-based tool, which may be due to a stiffer part in the membrane caused by a plastic welding line at this point.

4.2. Conical bowl mould

Based on the 3D measurement data, both tools performed well regarding the depth and steepness of the mould. The water-based tool achieves minor results compared to its MR-based equivalent, especially in the bottom corner of the mould's cavity. This is mainly due to the corner's radius being too small to be properly draped by the operator's fingers, which is not an obstacle for the MR-based tool since the pulling force exerted by the magnetic field is feature independent. Here, the limitation is imposed by the flexibility of the membrane's material. Compared to the state-of-the-art manual draping process without the use of additional tools, the water-based tool offers a reduction in distortions due to the even pressure distribution and support of the fibrous material provided by the membrane. Regarding the MR-based tool, even better results are obtained due to the

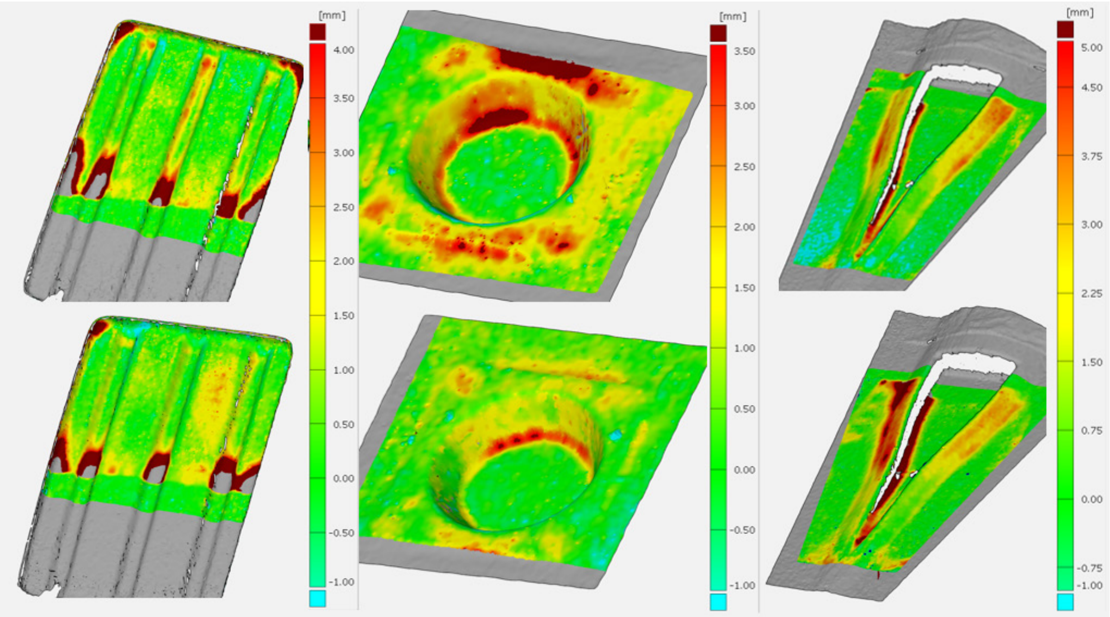

Fig. 6: 3D measurement data obtained by a ENSENSO stereovision 3D camera and inspected with the GOM Inspect software of a single layer twill-woven glass fibre sheet draped in three characteristic test moulds. Upper row: water-based results, lower row: MR-based results.

proper force distribution and inherent compliance of the magnetic pulling force on the MR fluid.

4.3. Air grabber mould

Analyses of the air grabber mould's 3D measurement data result in an opposite observation with regard to the conical mould, which could be caused by two main factors. Firstly, the air grabber mould is substantially thicker than the other two moulds, limiting the penetration depth and field strength of the magnetic field. Secondly, certain feature combinations can cause draping problems for the proposed tools, of which Figure 7 depicts an example mould and illustration showing two consecutive steep features creating a deep cavity in between. When the tool in placed on the mould, two fluid pockets will be formed on the outside of the steep features creating a tension force in the membrane which results in bridging over the central cavity. To alleviate this bottleneck, the tool's membrane bag should be contained on both sides to remove any undesirable tension force. Additionally, the fluid volume must be sufficient to fill the entire mould to the top of the highest feature in order to ensure correct tool operation. The MR-based tool's fluid volume was on the verge of being sufficient resulting in a poor result, but can of course be replenished to the correct amount in the future.

During the performed tests, unwanted fibre deformations were noticed after removing the tool from the mould, negating the previously made draping actions, which typically occurred when draping deep features, especially combined with vertical sides. This is caused by a higher friction coefficient between the tool and the fibre sheet compared to the friction coefficient between the fibre sheet and the mould. By adding an additional thin easily removable film between the fibre sheet and the tool during draping, this problem was resolved.

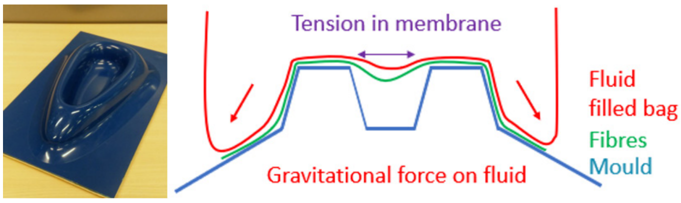

Fig. 7: Local bridging of the membrane due to a tension force caused by the formation of two fluid pockets on the outside of two steep features.

5. Discussion

The positive results of the proposed water-based draping tool prove its use as an assistive tool in manual composite part production, where its intrinsic holding capability serves multiple purposes. First of all, it eliminates the necessity of specific holding tools or weights which require additional operator actions. Secondly, the use of pre-treatment sprays to preclude springback of the fibre sheet can be reduced or possibly excluded, limiting the occurrence of defects in the finished product. This can also be attributed to the developed MR-based draping tool with the additional benefit towards fully automatic composite lay-up, providing an answer to the need for simple, cost-effective manipulation tools.

Future research tracks consist of extending the draping stage with an integrated gripping system for placing fibre sheets on the mould. This enables fully automatic lay-up and increases the control of fibre directions and prevents disruption of the fibres during handling. Automatic draping by means of the MR-based draping tool could be realised by providing a smart magnetic system underneath the mould. This could be done by an individually controlled magnetic grid with each pixel being a magnetic source or by mounting a magnetic source, preferably lightweight to limit the inertia of the system, on a robot's end effector. Here the draping strategy, respectively, the activation of the magnetic grid or the path planning of the robotic arm could be optimised. This, based on Multiphysics simulation data, for instance the applied stresses on the membrane and the fibre sheets caused by a magnetic flux distribution in the MR material and the attendant material stiffness change. Regarding the active material design, there are two possible tracks to be investigated. On the one hand, further optimising the MR-filled membrane, in particular improving the sedimentation stability of the magnetically permeable particles in the carrier liquid. On the other hand, fabricating a membrane made from MR elastomer, more specifically magnetically permeable particles in a silicone matrix. Besides this, inexpensive MR fluids in contrast to the contemporary commercially available MR fluids, and thin non-ferromagnetic moulds are key. The latter could be answered by single point incremental forming (SPIF) of aluminium moulds, by thin composite moulds or by the additive manufacturing (AM) of polymer or non-ferromagnetic moulds. Some initial positive prospects have been raised during tests towards multilayer draping. Nevertheless, further investigation is necessary regarding the consecutive lay-up of fibre sheets, one by one, and the lay-up of multiple fibre sheets at once. Additionally, the influence of gel-coated moulds on the draping process needs to be further explored. This gel coating will increase the mould's stickiness which in turn will increase the necessary draping force caused by a higher friction coefficient between the fibres and the mould. Finally, the third step of fixation (par. 3.1) can potentially be executed through integration of heating elements in combination with the use of a heat-activated binder. Hereby, the tool can also be used as a fully automatic preforming tool.

6. Conclusion

Composites have become more often the material of choice for a growing range of applications due to their high strength-to-weight ratio, high chemical resistance, design flexibility and durability. Unfortunately, cost-effective production remains a challenging factor in the emerging flexible high-mix, low-volume production scenarios. This is mainly caused by highly labour intensive manually handling and draping, due to difficult handling properties, the high variety and complexity of fibrous materials and the product contours. Even the current manipulation tools, for composite draping in moulds, often lack controllability and flexibility to cope with a high mix of features in the composite product. In automation, these problems are often answered by cost-increasing multi-robotic systems, using multiple degrees of freedom in combination with a large range of feature-specific tools. The need for simple, cost-effective manipulation tools triggered the development of a membrane-shaped magnetorheological (MR) based composite draping tool. Comparing the state-of-the-art systems with the manual draping process, one main action none have been able to imitate is distinguished. Namely, locally applying force in a continuous manner with a compliant tool whilst selectively fixating the remainder of the fibres in order to control shear and to ensure a satisfactory draped part. In the manual draping process this action is performed by the human operators' hands and fingers. The draping tools proposed in this paper aim to answer this shortcoming by a membrane-shaped water-based and MR-based tool to respectively enable human-robot collaboration (HRC), and to apply locally a magnetic attraction force and a tool stiffness change in order to enhance composite draping. The developed water-based and MR-based draping tools are tested on three characteristic moulds, namely a MDPE lid with reinforcement ribs, an aluminium conical bowl and a composite air grabber, and were able to deliver satisfactory results when draping a single layer of generic twill-woven glass fibre sheet. Here, the MR-based tool performed better at the level of narrow or corner-like features compared to the water-based tool.

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