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ORIGINAL ARTICLE

Design of a compliant device for peg-hole separation in robotic disassembly

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Abstract

Disassembly is the first step in the remanufacturing of a product. This paper presents the design of a robot end-of-arm tool for removing a peg from a hole, a common operation in the disassembly of mechanical products. The device is a compliant structure that enables the peg to be pulled out of a closely fitting hole without jamming or wedging. The device is reminiscent of the Remote Centre Compliance (RCC) mechanism used by assembly robots to insert cylindrical pegs into cylindrical holes with small clearances. However, whereas the RCC mechanism has primarily to withstand compressive forces, the proposed compliant device must resist tensile forces because of the nature of disassembly operations. The paper details a finite-element modelling study of peg removal with and without using the compliant structure. The results obtained show that the structure markedly reduces the stresses at the points of contact between the peg and the hole and, consequently, the risk of damage to the components being disassembled.

Keywords Robotic disassembly · RCC device · Peg-hole insertion · Peg-hole separation · Finite-element modelling · Automatic remanufacturing

1 Introduction

Remanufacturing can obtain the highest value of parts from used products, as well as a proportion of the original manufactured value to minimise environmental pollution and maximise resource utilisation [1]. A complete remanufacturing process comprises the following stages: disassembly, cleaning, inspection, repairing or replacing of damaged parts, reassembly and testing [2, 3].

1.1 Background

As the first and most important stage in the remanufacturing process, disassembly is the key link that connects product returns with product recovery [4, 5]. Although manual disassembly enables a precise disassembly operation that can protect components more effectively, it is inefficient. Automated disassembly with robotic devices can greatly reduce time and labour cost, which improves the efficiency of disassembly [6]. A critical problem that arises during component disassembly is that lateral and angular misalignment between the components being separated can produce large reaction forces. These reaction forces may lead to jamming and wedging, which would prevent the successful completion of the disassembly task and cause damage to the parts and robotic devices [7].

A compliant device, called Remote Centre Compliance (RCC), was invented at the MIT Draper Laboratories in the 1970s to solve jamming and wedging problems for 'peg-in-hole' insertion in robotic assembly. The device is to be mounted between the robot arm and the end effector to enable passive accommodation of the contact forces, allowing them to guide the insertion process [8, 9]. However, the original MIT's RCC device cannot be directly applied to the 'peg-out-of-hole' separation case in robotic disassembly because the large pulling load (i.e. tensile forces) generated between the upper and lower plates of the RCC device would damage its elastic beam structure. To overcome the structure complication and overweight limitation of conventional RCC devices (e.g. Compensator 9116 from ATI, Compensation unit AGE-XY from SCHUNK) when applied to peg-out-of-hole separation operation in robotic disassembly, a new compliant device with an improved

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structure of elastic deformation mechanism is proposed, in which laminated elastic beams in two layers under passive compression condition mainly contribute to the robotic manipulation operation of either peg-in-hole insertion or peg-out-hole separation.

During our R&D working on robotic disassembly in AUTOREMAN project, we focused on feasibility study of peg-hole separation with robots and conventional RCC devices to prevent from jamming and wedging problems. After failure of robotic disassembly test with KUKA LBR iiwa robot and ATI RCC device, we found that available RCC devices with single layer ESP beams is not suitable for robotic disassembly of pulling-out operation under large tensile load due to the shortcoming of laminated structure of the ESP, which was designed for robotic assembly of pressing-in operation under large compressive load. Based on advantages (e.g. variable lateral and axial stiffnesses of reliable ESP beams) and disadvantages (e.g. ESP's pins damages under large tensile load), we designed new compliant device of novel RCC prototype with two-layer ESP beams, which can be used for two robotic operations of pulling-out separation and pressing-in insertion under large compressive loads (i.e. passive compression conditions).

1.2 Literature review

1.2.1 Functionality and structure of the RCC device

Researchers have described several compliance concepts to enable robots to perform high-precision assembly tasks [10, 11]. A compliance strategy is passive accommodation, which uses an elastic structure to compensate for misalignments between the mating parts [12]. Contact forces arising when a part is being inserted into another cause elastic deformation of the compliant components in the structure to achieve this passive compensation function [13]. The RCC device is probably the best-known passive compliant device [14]. It was evaluated by General Motors and used in several assembly applications [15, 16].

The idea of the remote centre originated from the dynafocal method of supporting aircraft engines over 80 years ago [17]. The concept of a compliance centre located at the tip of the peg was proposed by Watson and Whitney [18]. At that point, contact forces and torques between mating parts, respectively, produce linear and rotational movements to accomplish the peg-in-hole assembly operation. Gustavson distinguished the types of contacts that may occur between the peg and the hole, namely, one-point contact, two-point contact and line contact. Two-point contact can cause different assembly issues during the insertion process [19].

However, if an RCC device is mounted between the robot's wrist and gripper, the compliance centre could be placed at the tip of the peg to ensure that the contact forces assist the robot in accomplishing the operation. The function of the RCC in peg-in-hole assembly depends upon the existence of a chamfer on either or both peg and hole surfaces to locate the mating parts initially relative to each other [20]. When the peg contacts the hole, reaction forces acting on the compliance centre only produce lateral motion without rotation, and moments only generate rotation about the compliance centre. This allows the insertion to be accomplished without jamming or wedging problems [21].

An RCC device used for assembly usually consists of two rigid plates, a top plate and a bottom plate, connected by elastic beams (see Fig. 1) [22]. In the unstressed state, the plates are parallel to each other [23]. In a top-down insertion scenario, the top plate is mounted on the wrist of the robot, while the bottom plate houses the gripper which holds the peg (the gripper is omitted from Fig. 1 where the peg is shown directly fixed to the bottom plate). The compliance centre is designed to be located at the tip of the peg. The positioning of the elastic beams projects a predetermined compliance centre remote from the bottom plate of the RCC device, which indicates that the position of the compliance

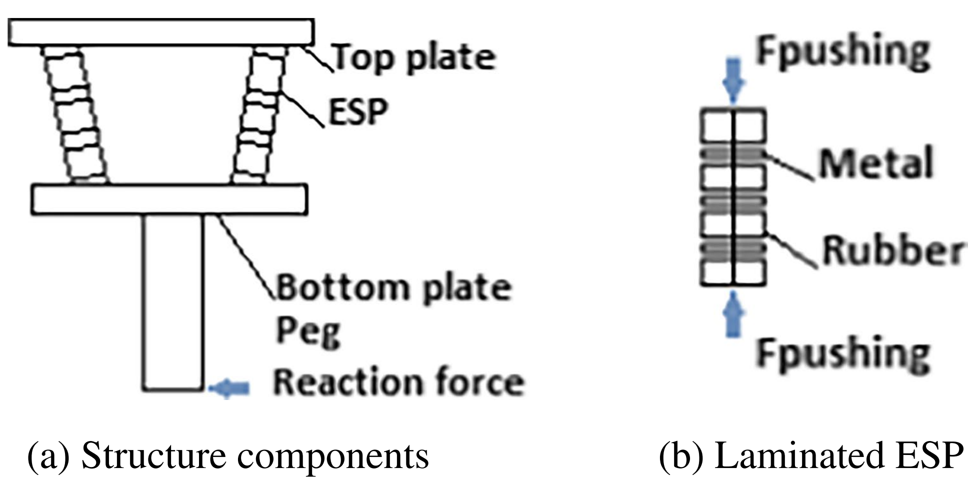


Fig. 1 A conventional RCC with ESP structure for peg-in-hole insertion

centre changes with the angle and the position of the elastic beams [24].

1.3 Properties of elastomeric shear pads

The elastic beams in an RCC device are usually elastomeric shear pads (ESPs). An ESP is a rubber-metal sandwich comprising alternating layers of rigid washers and elastomers [25]. This kind of arrangement can provide a structure relatively stiff in the axial direction yet soft in shear. Early analyses of RCC devices assumed that the ESPs were linear elements [26] with four main elastic constants: lateral stiffness, bending stiffness, lateral and bending coupling stiffness and torsional stiffness. However, Joo et al. found that this assumption was inadequate to explain the behaviour of an ESP and RCC because the stiffness of an ESP exhibits nonlinearity [27]. Lee proposed a modified ESP design using the dependence of an ESP's stiffness on shear stress to yield an RCC device with a variable compliance centre [28].

In this work, the properties of ESPs are regarded as linear to simplify calculations. However, due to their sandwiched construction, laminated ESPs can only withstand large compressive forces, not large tensile forces, and a conventional RCC device with single layer ESP beams would be damaged by large pulling forces during robotic disassembly.

1.4 Calculation of compliance centre

A large projection of the compliance centre and low stiffness of ESPs are two major factors that need to be considered when designing an RCC device [29]. Rebman proposed that trade-offs must be made between size, stiffness and projection because of the difficulties in achieving the desired requirements in a fixed diameter device [30]. A mathematical model was established by Whitney to describe the relationships between the projection of the compliance centre and the tilt angle, position and stiffness of ESPs [31], and the basic sizing decisions for an RCC design can be made based on those relationships [32].

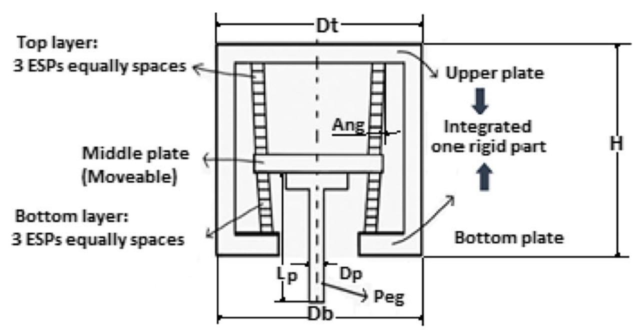
The remainder of the paper is organised as follows. Section 2 describes the design of the new compliant device for peg-out-of-hole operations. Section 3 discusses the finite element modelling of the device to determine the compliance centre and the stresses and deformations during disassembly. Section 4 presents the results obtained. Section 5 concludes the paper and gives suggestions for future work.

2 Design of new RCC device

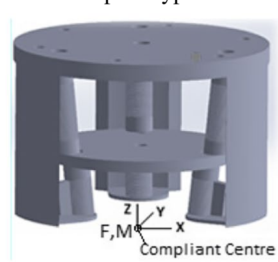
The new RCC device is inspired by the original device with a single layer of three ESPs arranged symmetrically in a circle and projecting a compliance centre below the bottom plate. As mentioned previously, the function of the ESPs is to absorb the forces and moments generated by peg-hole contact and provide compliance for the peg to compensate for misalignments during the insertion process. Owing to the laminated structure of ESPs, their extension is not restricted under pulling loads. This can lead to damage to the ESPs if the original RCC device is used for peg-out-of-hole operations.

The new RCC device comprises three plates and six ESPs. Unlike in the original RCC device, here, the upper plate and bottom plate of the new RCC device are integrated into one component. In addition, the peg is no longer mounted on the bottom plate but the middle plate. This restricts the extension of the ESPs and helps protect the ESPs from being damaged by high pulling forces.

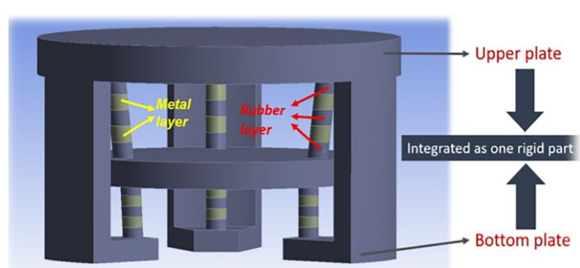
Figure 2a shows a sketch of the proposed RCC device. Figure 2b depicts its 3D CAD models. The ESPs in top layer can be seen in Fig. 2a as consisting of nine layers each, four of metal and five of elastomer. The ESPs in bottom layer can be seen in Fig. 2a as consisting of seven layers each, three



(a) Sketch of new RCC prototype with two layers of ESPs



(b) CAD models of the new RCC device



(c) Details of Elastomeric Shear Pad

Fig. 2 Proposed RCC device

of metal and four of elastomer. The next section looks at the finite-element modelling of the RCC device to find the compliance centre and the stresses and deformations in the peg and the hole during the disassembly operation.

3 Finite element modelling

Finite element modelling using ANSYS Workbench Version 19.1 was undertaken to show that the proposed device had a remote centre of compliance and to determine the location of that centre. The withdrawal of a cylindrical peg from a cylindrical hole with and without the assistance of the RCC device was then simulated to show the effect of using it on the resulting contact stresses and deformations in the components being separated.

3.1 Centre of compliance

Table 1a shows the key dimensions of the proposed RCC device and the construction details of its ESP shear pads. Table 1b gives the properties of the neoprene rubber used as the elastomer in the ESP shear pads. For simplicity, it was assumed that the deformations of the aluminium body of the RCC device (comprising the integrated upper and lower plates), the floating aluminium middle plate and the carbon steel (ASTM A307) shims in the ESPs were negligible.

A rigid peg of length l was fitted to the middle plate as shown in Fig. 2a. Forces and moments (F_x, F_y, F_z, M_x, M_y, M_z) were applied at/about the tip of the peg when the length l is varied. The translational and rotational movements of the peg in response to the exerted forces and moments were computed. The centre of compliance of the device was the point where an applied force caused the peg only to translate and an applied moment makes it rotate about that point.

Table 1 Geometric and material details of the proposed RCC device

(a) Geometric details of the RCC and ESPs	
RCC body	
Pitch circle diameter (top plate)	143 mm
Pitch circle diameter (middle plate)	56 mm
Pitch circle diameter (bottom plate)	62 mm
Distance between top and bottom plates	67 mm
ESPs	
Number of top ESPs	3
Number of bottom ESPs	3
Natural (unstressed) length of a top ESP	27 mm
Natural (unstressed) length of a bottom ESP	21 mm
Number of steel shims in top ESPs	4
Number of steel shims in bottom ESPs	3
Number of elastomeric layers in top ESPs	5
Number of elastomeric layers in bottom ESPs	4
Thickness of an elastomeric layer	3 mm
Thickness of a steel shim	3 mm
Diameter of top ESP cross-section	8 mm
Diameter of bottom ESP cross-section	8 mm
(b) Properties of the neoprene material in the ESPs	
Tensile range (*P.S.I*)	500 ~ 3000
Maximum elongation (%)	600
Initial shear modulus (*Pa*)	27,104

3.2 Preliminary experiment

In order to simulate the real situation of the peg-out-hole separation process, the initial settings and dimension of the peg and the hole should be based on the actual data measured from experimental test (see Fig. 3 and Table 2). The tolerance of the peg-hole and the mass of the peg are measured in the AUTOREMAN lab.

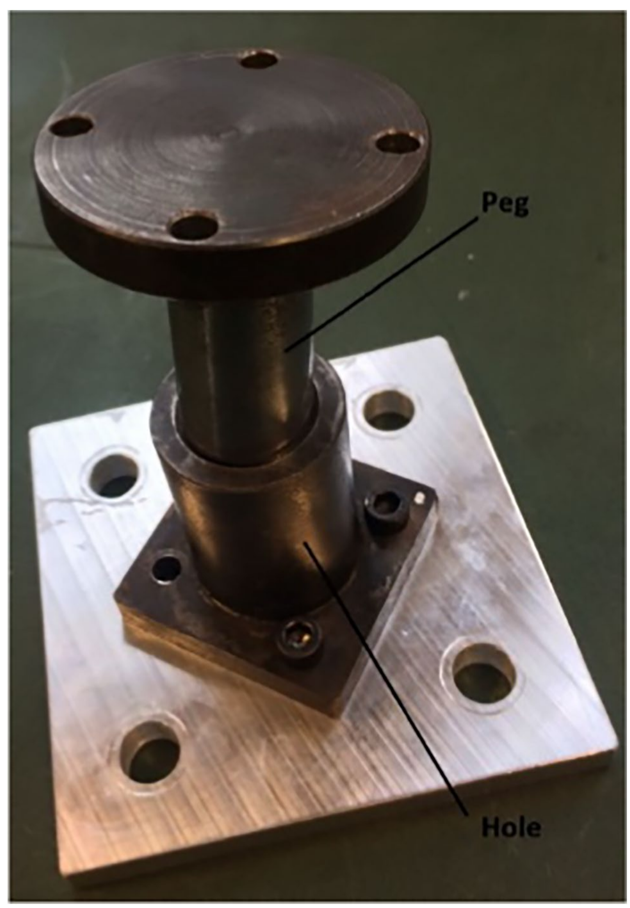


Fig. 3 Experimental test of fabricated peg and hole components in high-carbon steel for measurement

Table 2 Measured geometries and properties of the peg and the hole

Length of the peg (L_p)	70 mm
Diameter of the peg (D_p)	24.95 mm
Diameter of the hole (D_h)	25.05 mm
Materials of the peg and the hole (GB/T 1298)	high-carbon steel
Yield strength of the peg and the hole	525 MPa
Hardness of the peg and the hole	64 HRC

3.3 Contact stresses and deformations

Simulation was conducted of the withdrawal of a steel peg of length Lp = 70 mm and diameter $D_p = 24.95$ mm from a hole machined in a block of the same steel. The diameter of the hole was $D_h = 25.05$ mm. The steel used in the simulation was a high-carbon steel with a hardness of 64 HRC and a yield strength of 525 MPa. The coefficient of friction between the peg and the hole was 0.1. The direction of the withdrawal force was assumed to be 1.95 ° relative to the vertical axis. 1.95 ° is the jamming angle for the chosen peg-hole configuration [7]. As previously mentioned, two cases were investigated. In one case, the RCC device was not used, and the peg was fixed directly to the robot wrist (or rigidly held in the robot gripper). In the other case, the RCC device was fitted to the robot wrist, and the peg was mounted on the lower face of the middle plate.

4 Results and discussions

From Fig. 2a, based on tilted angle (Ang) and length of ESPs, the compliance centre is calculated and located at 71 mm from the bottom of the middle plate. A force exerted at that point will cause pure translation of the peg, and a moment around that point will make it rotate without translating.

Thus, for the given dimensions and geometry, the proposed device behaves as an RCC mechanism with a remote centre of compliance positioned 71 mm below the middle plate. The compliance matrix of the device expressed in a coordinate system located at the compliance centre is a diagonal matrix given by Eq. 1, in which $K_x = K_y = 420N/mm$, $K_z = 2.62N/mm$, $K_\alpha = K_\beta = 420Nmm/rad$ and $K_\gamma = 48.95Nmm/rad$.

$$[C] = \begin{bmatrix} Kx & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & Ky & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & Kz & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & K\alpha & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & K\beta & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & K\gamma \end{bmatrix} \quad (1)$$

As shown in Fig. 4 a and b, when the RCC device was not used, it is obvious that the peg could not be pulled out of the hole as the relative position between the peg and the hole did not change. Moreover, there was a huge equivalent stress change on the peg due to jamming as the direction of the withdrawal force was equal to the jamming angle (Fig. 5).

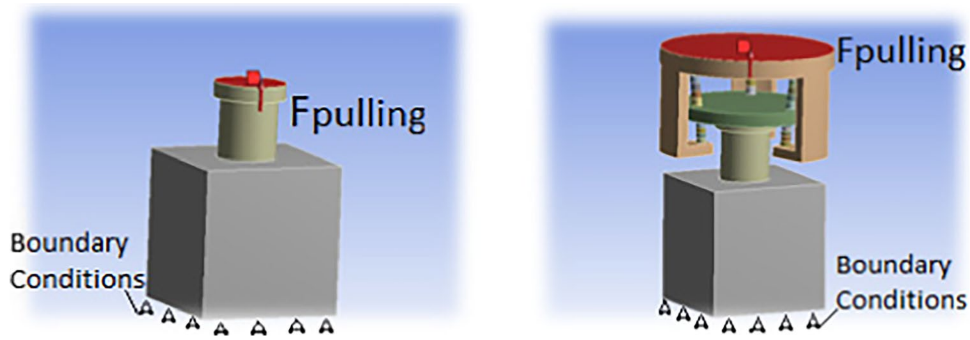
The FEM software gave a warning that the contact status had experienced an abrupt change during the simulation process (see the blue line in Fig. 6) and was unable to converge on a solution for this problem. As shown in Fig. 6, the maximum equivalent stress (represented by the green line) kept rising with time.

As shown in Fig. 7a, with the RCC device fitted, the peg could be completely pulled out of the hole. The stress distribution in the peg during the separation process can be seen in Fig. 7b. The stresses in the ESPs, especially at the connections between them and the middle plate, were significantly greater than the stresses in other components, causing them to deform, the middle plate to move and the peg to accommodate itself to the hole, thus facilitating the withdrawal process.

The stresses on the peg (see Fig. 7c) were much reduced when the RCC device was used, never approaching the material yield stress during the disengagement process. This shows the effectiveness of the device at preventing damage to components, enabling them to be reused following disassembly. It was also noted in the simulation that the contact state between the peg and the hole changed to one-point contact from two-point contact, which eliminated the possibility of wedging between the peg and the hole.

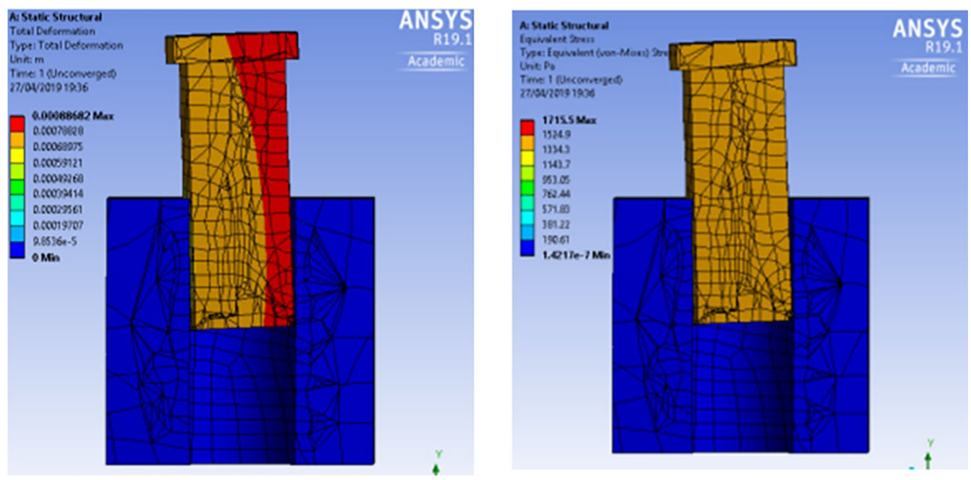
The colour of the stress map for the body of the RCC device (the integrated top and bottom plates) stayed blue during the whole separation process, which indicates that, throughout, there were negligible stresses in the body of the device. Therefore, it could be made of a suitably light aluminium alloy to keep the weight of the device down.

Figure 8 shows the evolution of deformations in the system. The red line represents the minimum deformation which remained close to zero during the disengagement of the pin from the hole. This indicates that there were parts of the system, notably, the body of the RCC device, where the deformation could be neglected, as previously assumed. The green line in Fig. 8 represents the maximum deformation in the entire geometry. This occurred at the ESPs where, according to Fig. 7b, stresses were also the highest, which shows the ability of the RCC device to absorb the load transferred to it during the disengagement of the peg from the hole. As the peg moved to conform to the position of the hole, the maximum deformation kept increasing until the peg became fully disengaged when all deformations became virtually null. Note that the initial deformations in the system were non-zero because it started from a stressed state with the peg and hole being misaligned relative to each



(a) Without RCC device (b) With RCC device

Fig. 4 The two case studies of peg-out-of-hole operation for FEM simulation (robot wrist not shown)



(a)Total deformation (b) Equivalent stress

Fig. 5 Simulation results for peg-out-of-hole operation without using a new RCC device

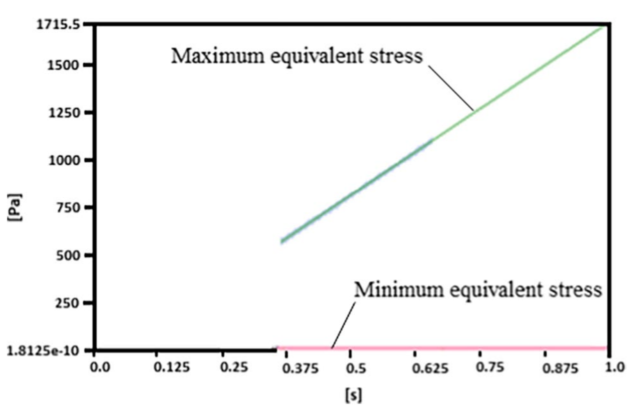
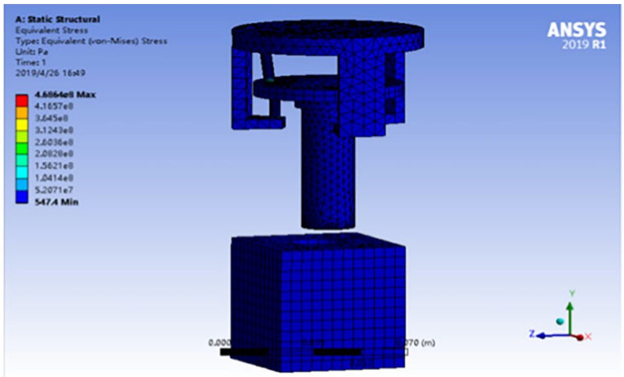


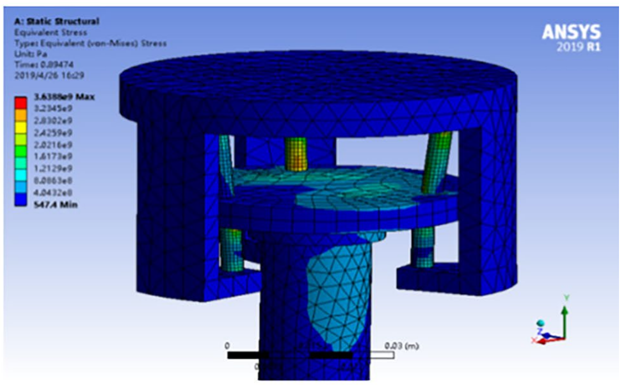
Fig. 6 Equivalent stress curve

other. The final deformations were also not exactly null as the weight of the peg caused the ESPs to remain slightly stretched or compressed even after full disengagement.

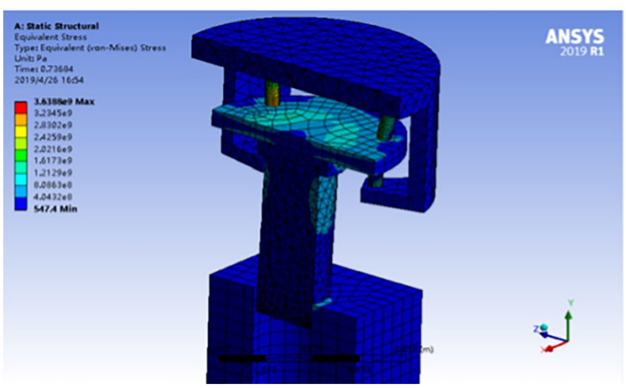
Figure 9 plots the stresses in the system. The red line in Fig. 9 represents the evolution in the minimum stress over the entire geometry, which confirms the previous observation that the minimum stress remained close to zero throughout the peg removal operation. The green line represents the maximum stress in the system. As mentioned above, stresses were highest in the ESPs and at the joints between them and the middle plate. The maximum stresses were well below the shear strength of the neoprene rubber in the shear pads as previously observed.



(a) Peg completely pulled out of hole



(b) Stresses on the ESPs and middle plate



(c) Stresses at contact points

Fig. 7 Simulation results for peg-out-of-hole operation with the new RCC device

Again, it can be noted that the green line in Fig. 9 does not start from zero due to the initial stressed state of the RCC device. The line does not drop fully to zero when the peg was completely removed from the hole. This is because there are still small residual stresses due to the weight of the peg transmitted to the ESPs via the middle plate of the RCC device.

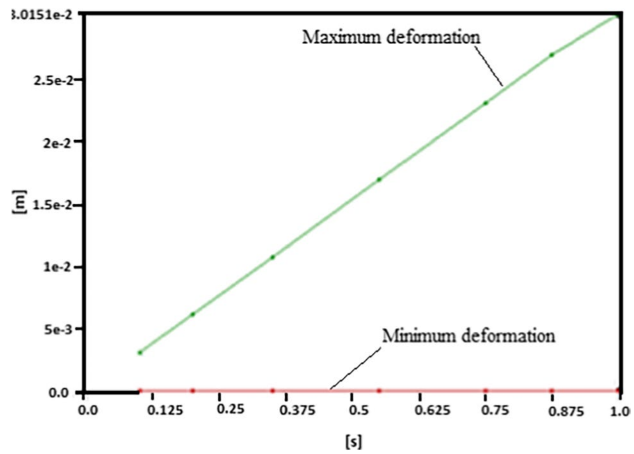


Fig. 8 Evolution of maximum and minimum deformations

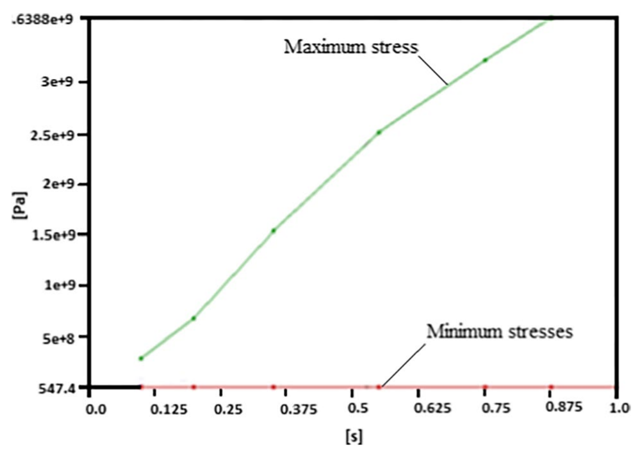


Fig. 9 Evolution of maximum and minimum stresses

The results obtained from this finite-element modelling work have shown that the proposed device has a remote compliance centre and the effect of fitting the device to the wrist of a robot is to enable it to remove a peg from a hole without jamming or wedging even when the peg-hole clearance is very small.

5 Conclusion and future work

Remanufacturing is an important part of a circular economy, saving raw material and energy and drastically reducing greenhouse gas emissions and the need for landfill space. The first operation in remanufacturing is the disassembly of the product to be remanufactured to recover its components for repair or, preferably, reuse. To preserve the maximum value of the components that are being disassembled, they must not be damaged during the disassembly process. For this reason, disassembly requires skills and, as products at the end of their service life tend to be difficult to disassemble, human operators are usually needed to perform disassembly tasks.

The work reported here was part of a research programme aimed at robotising disassembly [33]. The project began with an analysis of more than four hundred real products to determine frequently occurring disassembly operations. The removal of a peg from a hole, representing, for example, the disassembly of a shaft from a bearing in car turbocharges and electric motors, was found to be one such typical operation. It was thus chosen as the target for the present study; the aim of which was to design an end-of-arm tool to enable a robot to perform the operation without causing undue stresses in the peg or the hole.

The robotic device is a compliant structure that enables the peg to be pulled out of a closely fitting hole without jamming or wedging. The device was inspired by the Remote Centre Compliance (RCC) mechanism used by assembly robots to insert cylindrical pegs into cylindrical holes with small clearances. However, rather than compressive forces as in the case of peg-hole insertion, the proposed device must resist the tensile forces that occur as the peg is pulled away from the hole. To achieve this, the novel device was constructed with two layers of elastic shear pads (ESPs) instead of just one layer as in the original ATI's RCC device, with the peg rigidly fixed to a plate fitted between the two ESP layers.

The finite-element modelling study conducted shows that the centre of compliance of the device is located remotely from the plate holding the peg. As expected, at that location, the 6×6 compliance matrix of the device is diagonal. By appropriately choosing the dimensions of the device, it is possible to make the centre of compliance coincide with the tip of the peg. The simulated disassembly experiments without and with the device fitted to the wrist of the disassembly robot demonstrate the effectiveness of the device at keeping the stresses in the peg and the hole well beyond the level that can cause damage to them.

In addition to testing physical prototypes of the proposed RCC device in a real industrial environment, future work could proceed in two directions. First, the sensitivity of the performance of the device to the location of the centre of compliance should be investigated in detail and its range of operation maximised to cater for pegs of widely different lengths. Second, the feasibility of the device as a robotic tool to aid the undoing of threaded fasteners, the most common disassembly operation—twice as frequent as peg-hole removal [33]—should be studied. Because such unscrewing operations would involve torsional deformation, the device would probably need to be redesigned to give it greater torsional strength.

Collaborating with industrial remanufacturing partners in our AUTOREMAN project, our R&D tasks aim to implement to developed project prototypes in their real production. Currently, we are developing innovative robotic disassembly cells with sensor-base robots and improved RCC devices for automated separation and unscrewing operations of robotic disassembly for automated remanufacturing complicated products of car turbocharges and electric motors.

Author contribution The compliant device mechanism was proposed by Shizhong Su and Duc Truong Pham. The comments on the compliant device models and modelling simulation results were provided by Chunqian Ji, Yongjing Wang and Jung Huang. The CAD modelling and FEM simulation were performed by Wei Zhou and Haolin Wang in their final year projects. Their research of the peg–hole separation was supervised by Duc Truong Pham and Shizhong Su. Their experimental work of robotic disassembly process was supervised by Yongjing Wang and Jun Huang. The first draft of the manuscript was written by Shizhong Su and Duc Truong Pham, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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