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Standard PROPOSAL

Document Status: With Council
EPSRC Reference: EP/X037746/1

Organisation where the Grant would be held

Organisation	University of Birmingham	Research Organisation Reference:	Project 2115631
Division or Department	Mechanical Engineering		

Project Title [up to 150 chars]

Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)

Start Date and Duration

a. Proposed start date	01 July 2023	b. Duration of the grant (months)	36

Applicants

Role	Name	Organisation	Division or Department	How many hours a week will the investigator work on the project?
Principal Investigator	Dr Yongjing Wang	University of Birmingham	Mechanical Engineering	3.75
Co-Investigator	Dr Shiyang Tang	University of Birmingham	Electronic, Electrical and Computer Eng	1.88

Objectives

List the main objectives of the proposed research in order of priority [up to 4000 chars]

This proposed project aims to create novel mechanical compliance devices with tuneable stiffness along 6 axes (3 translational motions and 3 rotational motions) as well as tuneable rotational centres, underpinned by the recent discovery about the electro-mechanical properties of the Field's metal hybrid filler elastomer (FMHE).
The following objectives have been identified, which will be achieved through a structured work plan:
1. Developing novel shear pads using the FMHE and investigating their mechanical properties (Objective O1)
2. Investigation into the physical architecture and analytical modelling of the FMHE-based compliance devices using the shear pads developed by achieving O1 (Objective O2)
3. Developing the actuation and control techniques for the FMHE-based compliance devices developed by achieving O2 (Objective O3)

4. Prototype fabrication, demonstration and dissemination (Objective O4)

Summary

Describe the proposed research in simple terms in a way that could be publicised to a general audience [up to 4000 chars]. Note that this summary will be automatically published on EPSRC's website in the event that a grant is awarded.

Compliance facilitates the alignment of objects in automated assembly and disassembly. Compliance is a key technique to cope with uncertainties in positions and motions in automated operations. The stiffness of 6-axis compliance (3 translational motions and 3 rotational motions) and the location of centre-of-compliance can all affect the performance of assembly and disassembly (e.g. minimised friction or jamming).

There are two types of compliance for robotic assembly and disassembly: passive compliance and active compliance. Passive compliance is reliable, efficient but not flexible; active compliance is flexible but slow.

PROMOTE aims to combine passive compliance and active compliance to create HYBRID COMPLIANCE that can deliver high efficiency as well as high flexibility. Hybrid compliance is a novel mechanical compliance device with tuneable stiffness along 6 axes (3 translational motions and 3 rotational motions) as well as tuneable centre-of-compliance.

This research is underpinned by new research work carried out by Wang (PI) and Tang (Co-I) on a new type of metal-polymer composites (i.e. the FMHE) with self-triggered tuneable conductivity and stiffness. The new material research offers new material options for developing multi-axis tunability.

Hybrid compliance can be key to small-batch high-variation assembly (e.g. in aerospace, automotive and electronic industries) and disassembly (e.g. in recycling and remanufacturing) both of which require high efficiency as well as high flexibility, and in high demand for robotisation due to the labour shortage and the productivity gap.

Academic Beneficiaries

Describe who will benefit from the research [up to 4000 chars].

PROMOTE's main contributions will be (i) understanding the shear properties of the FMHE and (ii) novel compliance devices with tuneable compliance properties using the FMHE. The novelty of PROMOTE is detailed in the Programme and Methodology section.

Successfully achieving O1 and O2 will help mechanical engineers to design next-generation compliance devices with tuneable multi-axis compliance properties. The academic impact of the proposed research goes beyond mechanical engineering and into robotics, materials science and manufacturing engineering.

The use of the proposed compliance in assembly and disassembly will be of interest to researchers in mechanics and compliance mechanism (e.g. ETH Zurich, CAS Institute of Automation and Tsinghua). The studies on the FMHE will be of interest to researchers in dynamics and vibration (e.g. Wollongong, Tohoku), as well as soft material engineers (e.g. Bristol, Stanford, UNSW and Warwick). The use of robotics in assembly and disassembly may help academic research in manufacturing (e.g. Cambridge, KTH, Loughborough, Nottingham, Sheffield and Strathclyde), and research into the circular economy (e.g. the NICER programme), and a variety of sector-based research including aerospace, energy and railway.

Summary of Resources Required for Project

Financial resources

Summary fund heading	Fund heading	Full economic Cost	EPSRC contribution	% EPSRC contribution
Directly Incurred	Staff	195433.03	156346.43	80

Summary of staff effort requested

	Months
Investigator	5.25
Researcher	50
Technician	0
Other	0

	Travel & Subsistence	23500.00	18800.00	80
	Other Costs	50800.00	40640.00	80
	Sub-total	**269733.03**	**215786.43**	
Directly Allocated	Investigators	28566.30	22853.04	80
	Estates Costs	56411.00	45128.80	80
	Other Directly Allocated	15618.02	12494.42	80
	Sub-total	**100595.32**	**80476.26**	
Indirect Costs	Indirect Costs	254018.00	203214.40	80
Exceptions	Staff	0.00	0.00	100
	Other Costs	0.00	0.00	100
	Sub-total	**0.00**	**0.00**	
	Total	**624346.35**	**499477.09**	

Visiting Researcher	0
Student	0
Total	55.25

Other Support

Details of support sought or received from any other source for this or other research in the same field.
Other support is not relevant to this application.

Staff

Directly Incurred Posts

			EFFORT ON PROJECT							
Role	**Name /Post Identifier**	**Start Date**	**Period on Project (months)**	**% of Full Time**	**Scale**	**Increment Date**	**Basic Starting Salary**	**London Allowance (£)**	**Super-annuation and NI (£)**	**Total cost on grant (£)**
Researcher	Research Fellow 1	01/07/2023	18	100	N/A	01/10/2023	33309.00	0	17124.00	69866.52
Researcher	Research Fellow 2	01/11/2023	32	100	N/A	01/10/2024	33309.00	0	31297.00	125566.51
									Total	195433.03

Applicants

Role	Name	Post will outlast project (Y/N)	Contracted working week as a % of full time work	Total number of hours to be **charged** to the grant over the duration of the grant	Average number of hours per week **charged** to the grant	Rate of Salary pool/banding	Cost estimate
Principal Investigator	Dr Yongjing Wang	Y	10	495	3.8	58041	17412
Co-Investigator	Dr Shiyang Tang	Y	5	248	1.9	74210.08	11154
						Total	28566

Travel and Subsistence

Destination and purpose		Total £
Within UK	Travels and conferences (details available in Justification of Resources)	23500.00
	Total £	23500.00

Other Directly Incurred Costs

Description	Total £
Consumables	36000
Dissemination	6000
Recruitment	2000
Support for staff relocation	2000
Annual maintenance of facilities (e.g. robots)	4800.00
Total £	50800.00

Other Directly Allocated Costs

Description	Total £
Pool staff costs	8356.00
Infrastructure Technicians	7262.02
Total £	15618.02

Research Council Facilities

details of any proposed usage of national facilities
Research Council Facilities are not relevant to this application.

Human Participation

Would the project involve the use of human subjects?		Yes	No✔
	If yes, would equal numbers of males and females be used?	Yes	No✔
Would the project involve the use of human tissue?		Yes	No✔
Would the project involve the use of biological samples?		Yes	No✔
Would the project involve the administration of drugs, chemical agents or vaccines to humans?		Yes	No✔
Will personal information be used?		Yes	No✔
	If yes, will the information be anonymised and unlinked?	Yes	No✔
	Or will it be anonymised and linked?	Yes	No✔
	Will the research participants be identifiable?	Yes	No✔
Please provide details of any areas of substantial or moderate severity:			

Animal Research

Would the project involve the use of vertebrate animals or other organisms covered by the Animals (Scientific Procedures) Act?		Yes	No✔
	If yes, what would be the maximum severity of the procedures?	Mild or non-recovery	
		Moderate	
		Severe	
	Please provide details of any areas which are Moderate or Severe:		

Animal Species
Does the proposed research involve the use of non-human primates? Yes ✔No

Does the proposed research involve the use of dogs?	Yes	✔No
Does the proposed research involve the use of cats?	Yes	✔No
Does the proposed research involve the use of equidae?	Yes	✔No

Please select any other species of animals that are to be used in the proposed research.

Fish	Sheep
Rabbit	Rat
Amphibian	Poultry
Cow	Mouse
Reptile	Guinea Pig
Pig	Other Rodent
Bird	Other Animal

Genetic and Biological Risk

Would the project involve the production and/or use of genetically modified animals?	Yes	✔	No
If yes, will the genetic modification be used as an experimental tool, e.g., to study the function of a gene in a genetically modified organism?	Yes	✔	No
And will the research involve the release of genetically modified organisms?	Yes	✔	No
And will the research be aimed at the ultimate development of commercial or industrial genetically modified products or processes?	Yes	✔	No
Would the project involve the production and/or use of genetically modified plants?	Yes	✔	No
If yes, will the genetic modification be used as an experimental tool, e.g., to study the function of a gene in a genetically modified organism?	Yes	✔	No
And will the research involve the release of genetically modified organisms?	Yes	✔	No
And will the research be aimed at the ultimate development of commercial or industrial genetically modified products or processes?	Yes	✔	No
Would the project involve the production and/or use of genetically modified microbes?	Yes	✔	No
If yes, will the genetic modification be used as an experimental tool, e.g., to study the function of a gene in a genetically modified organism?	Yes	✔	No
And will the research involve the release of genetically modified organisms?	Yes	✔	No
And will the research be aimed at the ultimate development of commercial or industrial genetically modified products or processes?	Yes	✔	No

Approvals

Have the following necessary approvals been given by:			
The Regional Multicentre Research Ethics Committee (MREC) or Local Research Ethics Committee (LREC)?	Yes	No	Not required✔
The Human Fertilisation and Embryology Authority?	Yes	No	Not required✔
The Home Office (in relation to personal and project licences, and certificates of designation)?	Yes	No	Not required✔

The Gene Therapy Advisory Committee?	Yes	No	Not required✔
The UK Xenotransplantation Interim Regulatory Authority?	Yes	No	Not required✔
Administration of Radioactive Substances Advisory Committee (ARSAC)?	Yes	No	Not required✔
Other bodies as appropriate? Please specify.			

Other Issues

Are there any other issues of which the Council should be aware?	No

Provide details of what they are and how they would be addressed [up to 1000 characters]

Project Partners: details of partners in the project and their contributions to the research. These contributions are in addition to resources identified above.

1	Name of partner organisation		Division or Department	Name of contact	
Boston Dynamics			Academia and Research	Mr Ed Colp	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	Attening steering meetings	8000
secondme nt of staff			other		
other			Sub-Total		8000
Sub-Total		0		Total Contribution	8000

2	Name of partner organisation		Division or Department	Name of contact	
The Manufacturing Technology Centre Ltd			Research	Dr Helen Finch	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		
equipment/ materials			staff time	Attendng steering meetings and support with a case study	30000
secondme nt of staff			other		
other			Sub-Total		30000
Sub-Total		0		Total Contribution	30000

3	Name of partner organisation		Division or Department	Name of contact	
Satellite Applications Catapult			Head Office	Mr Paul Febvre	
Direct contribution to project			**Indirect contribution to project**		
	Description	**Value £**		**Description**	**Value £**
cash			use of facilities/ equipment		

equipment/ materials			staff time	Attendng steering meetings and support with a case study	22000
secondment of staff			other		
other			Sub-Total		22000
Sub-Total		0		Total Contribution	22000

Total Contribution from all Project partners £60000

Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)

School of Engineering, University of Birmingham (UoB)

Section 1: Track Records

Dr Yongjing Wang (Principal investigator; CEng; BEng in Electronic/Electrical/Control Engineering; PhD in smart composite materials; Postdoc in applied robotics) is an Assistant Professor in the Department of Mechanical Engineering, School of Engineering, UoB. Wang's research focuses on a new generation of robotics technologies that improve the productivity and sustainability of industrial/manufacturing activities. Wang has multidisciplinary expertise in assembly/disassembly mechanics[1], automation and control engineering[2,3], human-robot collaborations[4,5], process planning and optimisation[6-9], and smart material engineering[10,11]. He is a Chartered Engineer with the Institution of Engineering and Technology and a Fellow of the Higher Education Academy.

Wang is the Principal Investigator of the EPSRC New Investigator Award on self-learning manufacturing robotics (ATARI, £300k, EP/W00206X/1) and high-TRL industrial projects. Wang is also a Co-investigator of the £6.7m Smart Factory Hub (SmartFub), a technology support scheme for small-to-medium manufacturers primarily funded by the European Regional Development Fund. In SmartFub, Wang contributes to and supervises industrial projects in robotics and automation.

Wang's recent research on **robotics and automation** has been published by learned journals, including *IEEE Transactions on Automation Science and Engineering*[3,9], *Robotics and Computer-Integrated Manufacturing*[6], *International Journal of Production Research*[11], *Journal of Manufacturing Systems*[7], and *Royal Society Open Science*[1,10]. Wang has in total co-authored 37 papers published/accepted by journals and conferences. Wang is also a co-author of a book published by Springer in the area of robotic disassembly[12].

Dr Shi-yang Tang (Co-investigator; BEng in Electrical Engineering; PhD in Microelectromechanical Systems) is an Assistant Professor at the Department of Electronic, Electrical and Systems Engineering, School of Engineering, UoB. Tang worked on surface acoustic wave enabled electromechanical platforms as a postdoctoral researcher at Pennsylvania State University from 2015 to 2016. Later, he joined the University of California, San Francisco (UCSF) and worked on droplet-based microfluidics for point-of-care diagnosis from 2016 to 2017. From 2017 to 2020, he was the Vice-Chancellor's Postdoctoral Research Fellow at the University of Wollongong, Australia, worked on smart materials enabled electromechanical sensors and actuators. Tang is the recipient of the Discovery Early Career Researcher Award (DECRA, $355,000 AUD) from the Australian Research Council (ARC), the PI of a project directly funded by industry (~£275,000), the PI of the Discovery Project Grant from the ARC ($420,000 AUD), the PI of the Royal Society International Exchange project (£11,800), and the Co-I of the Standard Research Grant from the EPSRC (£446,110).

Tang's recent research on **smart composite materials and soft robotics** has been published in journals such as *Nature Communications*[13], *Matter*[14], *Advanced Materials*[15,16], *Advanced Science*[17], and *Proceedings of the National Academy of Sciences*[18].

Recent works relevant to the proposal

Wang has a track record of research in the area of **robotics for remanufacturing** (e.g. postdoc, AUTOREMAN, EP/N018524/1; and PI, ATARI, EP/W00206X/1). He played an instrumental role in the practical development of three robotic systems that can disassemble high-value automotive components. He has hands-on experience in many activities in the development of automation systems, e.g. design, integration, software development and hardware implementation. Wang is an elected member of the UK-RAS (robotics and autonomous systems) early-career forum.

The focus of Wang's previous work was to develop hardware facilities and control/planning strategies to **overcome uncertainties in robotic assembly and disassembly**. For example, Wang's work has contributed to the building of a dexterous robotic system that can remove bolts and nuts under major uncertainties (e.g. misalignment and jamming)[3].

Tang has a track record of research in the area of smart composite materials with a focus on liquid metal hybrid composites. Recent research led by Tang created a new type of metal-polymer composites with self-triggered switchable conductivity and stiffness[19]. This research investigates

Case for support

the Field's metal hybrid filler elastomer (FMHE) that shows high-range variable and tuneable properties (up to 10 times) in conductivity, strain sensitivity, and stiffness. The unusual electromechanical properties of the FMHE have not been observed in other types of smart composite materials. The creation of the FMHE offers a new option in the design of compliance devices with multi-axis tunability which can be applied to robotic assembly and disassembly processes.

Synergies with research environment

UoB's active research in robotics includes but is not limited to soft robotics (Nefti-meziani), visual recognition (Chang), robotic grasping (Stolkin), multi-robot planning (Mansouri), and the application of robots to manufacturing (Pham) and Railway (Stewart and Dixon). This project will invite them to attend the project advisory meetings to explore new applications of the proposed compliance device.

This project will benefit from the state-of-the-art robotic lab, cleanroom and the process room all of which are available within the school and can be used in this project for free. In particular, UoB has also recently invested £2M to upgrade the cleanroom and the process room, strengthening the capability in microfabrication of composite materials, MEMS, and soft sensors/actuators. This facility hosts Tang's Soft Intelligent Systems lab with dedicated fabrication bench, material testing systems, electronic testing equipment, and a specialist inverted microscope equipped with a high-speed camera to study the composite materials.

The Exchange, UoB's new city hub, can be used for exhibitions or demonstrations to members of the public. The university also offers a variety of internal funds to encourage public engagement and showcase research to local industry.

Boston Dynamics (BD) is a project partner - the UoB and BD are working jointly on the use of legged robots for infrastructure repair and maintenance which will involve complex assembly and disassembly operations. BD will be involved in a case study in PROMOTE.

Satellite Applications Catapult (SAC) is a project partner – As one of the nine Catapults, SAC supports the development of technologies to enable the removal of space debris, servicing & assembly of new space craft and manufacturing in space through the use of robotics with its terrestrial and proposed space-based facilities.

The Manufacturing Technology Centre (MTC) is a project partner – As a high-value manufacturing catapult, MTC will work with the team to enable the exploitation of the research from TRLs 1-4 into applications through TRLs 5-7 with potential end uses to various sectors. Personnel from within two themes: Intelligent Automation and Sustainability at the MTC will be involved.

National Robotics Network (NRN) is a supporter of PROMOTE (support letter attached). NRN will offer a network of industry end users, supply chain and academic organisations for PROMOTE to develop case studies and plan follow-on developments of high TRL.

References

1. Zhang, Y., *et al. Royal Society open science* 6.8 (2019): 190476. **2.** Liu, Q., *et al. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (2022): 09544054221076233. **3**. Li, R., *et al. IEEE Transactions on Automation Science and Engineering* 17.3 (2020): 1455-1468. **4.** Huang, J., *et al. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 234.3 (2020): 654-664. **5**. Huang, J., *et al. Computers & Industrial Engineering* 155 (2021): 107189. **6**. Ye, F., *et al. Robotics and Computer-Integrated Manufacturing* 78 (2022): 102392. **7**. Laili, Y., *et al. Journal of Manufacturing Systems* 60 (2021): 214-225. **8.** Wang, Y., *et al. International Journal of Production Research* 59.15 (2021): 4723-4735. **9**. Laili, Y., *et al. IEEE Transactions on Automation Science and Engineering* (2021). **10**. Wang, Y*., et al. Royal Society open science* 3.9 (2016): 160488. **11.** Deng, S., *et al.* "Laser directed writing of flat lenses on buckypaper." *Nanoscale* 7.29 (2015): 12405-12410. **12**. Laili, Y., Wang, Y. W., Fang, Y., & Pham, D. Optimisation of Robotic Disassembly for Remanufacturing. (1 ed.) (Springer Series in Advanced Manufacturing). Springer, Cham (2021). **13**. Yun, G., *et al. Nature communications* 10.1 (2019): 1-9. **14**. Yun, G., *et al. Matter* 3.3 (2020): 824-841. **15**. Wu, J., *et al. Advanced materials* 30.51 (2018): 1805039. **16**. Jian, S. *et al. Advanced Materials* 33, no. 43 (2021): 2103062.**17**. Li, X. *et al. Advanced Science* 9, no. 11 (2022): 2105289. **18**. Tang, S., *et al. Proceedings of the National Academy of Sciences* 111.9 (2014): 3304-3309. **19**. Yun, G., *et al.* "Electro-mechano responsive elastomers with self-tuneable conductivity and stiffness*" under review, preprint available at: https://www.researchsquare.com/article/rs-2039368/v1*.

Case for support

Section 2: Project Description

Summary: Compliance facilitates the alignment of objects in automated assembly and disassembly. Compliance is a key technique to cope with uncertainties in positions and motions in automated operations. The stiffness of 6-axis compliance (3 translational motions and 3 rotational motions) and the location of centre-of-compliance can all affect the performance of assembly and disassembly (e.g. minimised friction or jamming).

There are two types of compliance for robotic assembly and disassembly: passive compliance and active compliance. Passive compliance is reliable, efficient but not flexible; active compliance is flexible but slow.

PROMOTE aims to combine passive compliance and active compliance to create HYBRID COMPLIANCE that can deliver high efficiency as well as high flexibility. Hybrid compliance is a novel mechanical compliance device with tuneable stiffness along 6 axes (3 translational motions and 3 rotational motions) as well as tuneable centre-of-compliance.

This research is underpinned by new research work carried out by Wang (PI) and Tang (Co-I) on a new type of metal-polymer composites (i.e. the FMHE) with self-triggered tuneable conductivity and stiffness (see Section 1 Track Record). The new material research offers new material options for developing multi-axis tunability.

Hybrid compliance can be key to small-batch high-variation assembly (e.g. in aerospace, automotive and electronic industries) and disassembly (e.g. in recycling and remanufacturing) both of which require high efficiency as well as high flexibility, and in high demand for robotisation due to the labour shortage and the productivity gap.

2.1 Background

In mechanical and manufacturing engineering, compliance offers flexibility in force and motion transmission through body deformation. Compliance offers some degree of freedom in motion rather than from rigid-body joints alone.

Compliance is critical to industrial automation, in particular in robotic assembly and disassembly processes where uncertainties in positions may cause misalignments between mating components, and thus compliance devices are needed to offer passive motion accommodation. The stiffness of 6-axis compliance (3 translational motions and 3 rotational motions) and the location of centre-of-compliance can all affect the performance of assembly and disassembly (e.g. minimised friction or jamming). Compliance is also important to robot safety (e.g. soft and safe collision).

There are two types of compliance for robotic assembly and disassembly: passive compliance and active compliance. Passive compliance is a peripheral device that attaches a to robot wrist or body, allowing the robot to interact with its task or environment through the device. Passive compliance is usually designed for *mass assembly* (i.e. repetitive high-volume assembly operations) and they usually have fixed compliance properties (i.e. stiffness and centre-of-compliance). Active compliance is commonly achieved via the software programming of the servo joints and uses sensors (e.g. vision, force and torque ones). Passive compliance is reliable, efficient but not flexible; active compliance is flexible but slow[1-3].

The growing activities in small-batch high-variation assembly (e.g. in aerospace, automotive and electronic industries) and disassembly (e.g. in recycling and remanufacturing) are in demand of next-generation compliance devices with high efficiency as well as high flexibility. In particular, recycling and remanufacturing underpin *circular economy* and *sustainable manufacturing*.

The vision for this proposal is to combine passive compliance and active compliance to create *Hybrid Compliance* – novel mechanical passive compliance devices with tuneable and programmable compliance properties.

There has been some preliminary research into tuneable passive compliance developed by engineers in Korea[4], Japan[5] and China[6]. But they tended to focus on *ad hoc* applications and the tunability is limited (e.g. only selected axes are tuneable). Programmable compliance properties in all six axes are needed due to the high-level dexterity required in both assembly and disassembly.

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We have seen significant research efforts in the development of next-generation industrial robotics (e.g. speed, lightweight and safety). However, compliance devices as useful components of industrial automation have been overlooked and there has been no major research investment into compliance devices to meet the demands for high-variation assembly and disassembly.

A key technical challenge to develop hybrid compliance is the lack of suitable materials and mechanisms to construct the tuneable stiffness along 6 axes (3 translational motions and 3 rotational motions) and tuneable rotational centres. The new material research led by Tang (see Section 1 Track record) offers new material options for developing multi-axis tunability.

We anticipate seeing that hybrid compliance may also be used in other applications such the automated docking systems for spacecrafts, and the tasks that involve complex manipulation, e.g. repair and maintenance - service robotics for repair and maintenance have been identified as a key to future cities and transportation.

2.2 National importance

This interdisciplinary research proposal has the potential for impact across multiple EPSRC priority areas. The proposed project strongly aligns with the EPSRC themes on Engineering (Robotics and Artificial Intelligence Technologies), and Manufacturing the Future. PROMOTE's output about robotic disassembly fits the EPSRC's long-term vision on sustainable manufacturing.

The proposed compliance devices will encourage more use of robots in assembly (e.g. automotive, aerospace, electronics, etc.) and disassembly (e.g. repairs, remanufacturing and recycling). Techniques developed in PROMOTE have the potential to be applied to many EPSRC-funded developments involving high-level dexterity robotic manipulations and interactions, such as manipulator development led by Glovnea at Sussex, grasping led by Webb at Edinburgh, and picking-and-packing led by Dogar at Leeds, and by those incorporated in key EPSRC centres (e.g. EPSRC centres for agri-food robotics at Lincoln and for nuclear at Manchester). In particular, this project will complement the EPSRC's investment in remanufacturing robotics at the UoB (AUTOREMAN and ATARI).

The team at UoB has been awarded industrial contracts for our previous works on robotic disassembly and we anticipate seeing a growing demand for the robotisation of assembly and disassembly tasks in the coming years due to the reshoring of manufacturing and the high demand for manufacturing automation.

The proposed programme will contribute towards filling a gap about compliance design and development. With the EPSRC support, we will seek follow-on funding to capitalise on this competitive advantage by PROMOTE as in a model adopted by technology companies for high-value end-effectors (e.g. Shadow and ATI).

2.3 Research hypothesis and objectives

This proposed project aims to create novel mechanical compliance devices with tuneable stiffness along 6 axes (3 translational motions and 3 rotational motions) as well as tuneable rotational centres, underpinned by the recent discovery about the electro-mechanical properties of the FMHE.

The following objectives have been identified, which will be achieved through a structured work plan:

1. Developing novel shear pads using the FMHE and investigating their mechanical properties (Objective **O1**)
2. Investigation into the physical architecture and analytical modelling of the FMHE-based compliance devices using the shear pads developed by achieving **O1** (Objective **O2**)
3. Developing the actuation and control techniques for the FMHE-based compliance devices developed by achieving **O2** (Objective **O3**)
4. Prototype fabrication, demonstration and dissemination (Objective **O4**)

2.4 Contribution to knowledge

PROMOTE's main contributions will be (i) understanding the shear properties of the FMHE and (ii) novel compliance devices with tuneable compliance properties using the FMHE. The novelty of PROMOTE is detailed in the Programme and Methodology section.

Successfully achieving **O1** and **O2** will help mechanical engineers to design next-generation compliance devices with tuneable multi-axis compliance properties. The academic impact of the

Case for support

proposed research goes beyond mechanical engineering and into robotics, materials science and manufacturing engineering.

The use of the proposed compliance in assembly and disassembly will be of interest to researchers in mechanics and compliance mechanism (e.g. ETH Zurich, CAS Institute of Automation and Tsinghua). The studies on the FMHE will be of interest to researchers in dynamics and vibration (e.g. Wollongong, Tohoku), as well as soft material engineers (e.g. Bristol, Stanford, UNSW and Warwick). The use of robotics in assembly and disassembly may help academic research in manufacturing (e.g. Cambridge, KTH, Loughborough, Nottingham, Sheffield and Strathclyde), and research into the circular economy (e.g. the NICER programme), and a variety of sector-based research including aerospace, energy and railway.

2.5 Programme and methodology

The project's three-year research programme will comprise four work packages.

WP 1 (addressing **O1). The FMHE shear pads** (Lead: Tang; Support: Wang) (*Months*: 1-18)

A compliance device's stiffness is usually *non-homogeneous* – they are rigid along the axes that require high precision and soft along the axes that have uncertainties in positioning or motion and thus require compliance.

Compliance devices can be generally categorised into three types: lateral compliance devices, six-axis compliance devices, and Remote Compliance Centre (RCC) devices.

Lateral compliance devices offer X-Y lateral compliance and is usually rigid in Z-axis as well as all rotational axes. Both six-axis compliance and RCC devices offer compliance in six axes (i.e. X-Y-Z lateral and X-Y-Z rotation) but the key difference between the two is the centre-of-compliance – the former at the centre of the tool root and the latter at a projected remote location. The former is more generally used in bin picking, loading and unloading, polishing, and finishing; while the latter is usually used in contact-rich operations, e.g. peg-in-hole assembly and disassembly operations.

Shear pads are the enabling components of RCC devices. A shear pad is usually made of elastomers bonded between a series of steel shims – this architecture makes a shear pad rigid in compression, and relatively soft in tension and shear. The differences in shear pads' compression, tension and shear properties create *non-homogeneous compliance*. Another key feature of using shear pads is that they enable the creation of a remote centre-of-compliance which is critical to the autonomous alignments of components in assembly and disassembly operations[1,4,8].

Fig. 1 shows an example use of shear pads in an RCC and the deformation of shear pads allows the alignment of mating components in mechanical assembly.

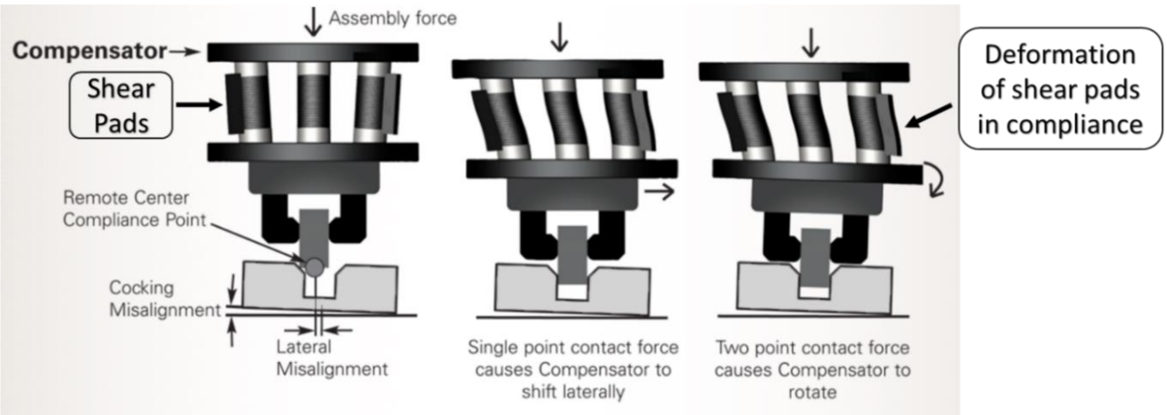

Fig. 1 Example of an RCC using shear pads[9]

Shear pads' mechanical performance is fixed and thus RCC devices have fixed compliance properties (i.e. fixed stiffness and location of centre-of-compliance). The limitation of shear pads is becoming obvious as more automation and robotic operations are required to be flexible where manipulation objects and motion plans are uncertain. For example, for different peg-hole assembly and disassembly operations, the location of centre-of-compliance and lateral stiffness need to be adjusted for different peg-hole clearance, length and materials[1]. This high-level flexibility cannot be delivered using the current shear pads.

Case for support

This work package will carry out an in-depth investigation into the properties of FMHE and use the obtained knowledge to create new shear pads.

Task 1.1 Investigating into the shear properties of the FMHE (Months 1-6). **Methods:** The FMHE comprises the primary Fields metal (FM) microparticle filler and a secondary solid metal microparticle filler (such as nickel or iron). These fillers are dispersed in a polymer matrix. The FM microparticle filler allows for the tuning of stiffness via phase change induced by Joule heating, while the secondary filler gives the FMHE piezoresistive property, high strain sensitivity, and improved microstructural strength and mechanical stability[10,11]. Built on the theoretical and experimental works we did to understand the compressive and tensile properties of the FMHE, we will carry out new investigations into the shear properties of the FMHE – this will involve analytical modelling, simulations and experimental validation. We will also investigate a range of the FMHE compositions to understand the range of the FMHE shear performance which will provide guiding information in the design of the FMHE shear pads.

Task 1.2 New design of shear pads using the FMHE (Months 7-12). **Methods:** We will adopt two methods to design the FMHE shear pads with tuneable stiffness along different axes: (1) the analytical modelling tools that have been used in the design of conventional shear pads[8]; and (2) a generative approach using modern computational tools and topological optimisations[12,13]. We consider that (1) is conservative and successful modelling methods have been established; (2) is more adventurous but this strategy was not available when shear pads were created, and this method has the potential to create new shear pad structures and architectures that have not been seen via conventional modelling methods.

Task 1.3 Fabrication and validation of the FMHE shear pads (Months 7-18). **Methods:** Based on the knowledge gained in Tasks 1.1 and 1.2, we will build and test the proposed FMHE shear pads. The fabrication of stretchable components can be completed at Tang's lab and their mechanical performance will be tested and validated using the mechanical testing facilities within the School of Engineering, UoB.

Novelty: The novelty of this work package is twofold: (1) This is the first research investigating the shear property of the FMHE - a new type of composite material that has shown extraordinary electromechanical properties (e.g. high-range tuneable stiffness); (2) the design of shear pads has been established for decades and this research is the first to look at improving the performance of shear pads using active materials and computational tools.

Deliverable 1.1: The mechanical performance of the FMHE as compliance materials (Month 6)**;**
Deliverable 1.2: Fabricated FMHE shear pads (Month 18)

WP 2 (addressing **O2). The FMHE compliance devices** (Lead: Wang; Support: Tang) (*Months*: 1-24)

As being discussed in WP1 there are three main types of compliance devices: lateral, six-axis and RCC. Modifying lateral compliance device to achieve tuneable stiffness is relatively easy and thus is NOT the focus of PROMOTE.

This work package will develop six-axis compliance and RCC devices using the FMHE. In particular, having centre-of-compliance tuneable is the main technical challenge. We have demonstrated a pilot study using FMHE to build robotic compliance[14]; however, we have not investigated the tunability of the new compliance mechanism.

Task 2.1 Design and modelling of hybrid compliance with tuneable stiffness and centre-of-compliance (Months 1-24). **Methods:** We will adopt classic methods that have been utilised in the design and modelling of existing compliance devices[8] but using the parameters of the FMHE. We will consider a variety of the FMHE designs (e.g. the FMHE shear pads developed in WP1 as well as the FMHE cylindrical and cubic blocks). For the forces applied to compliance devices considered to be conservative, we will use classic kinematic and dynamic methods for modelling. For analysis methods beyond the scope of classic analytical methods, we will adopt computational tools combing machine learning and finite-element analysis to quantify the compliance performance of the FMHE compliance devices in simulated environments.

Task 2.2 Fabrication and validation of hybrid compliance with tuneable stiffness and centre-of-compliance (Months 13-30). **Methods:** Similar to what we planned in Task 1.2, the fabrication of the FMHE compliance devices can be completed at the process room facilities at UoB and their

Case for support

compliance performance will be tested and validated using the methodology developed in AUTOREMAN[1].

Novelty: The main novelty of this work package is the creation of new knowledge, design and mechanism of compliance devices to achieve tuneable stiffness along multiple axes and centre-of-compliance, enabled by the FMHE.

Deliverable 2: Validated compliance devices (i.e. two types: six-axis and RCC) with tuneable stiffness and centre-of-compliance.

WP 3 (addressing **O3). Control techniques and strategies** (Lead: Wang; Support: Tang) (*Months*: 13-30)

Based on the development in WP2, this work package aims to build actuation and control strategies for the proposed FMHE compliance devices. The focus is to control 1) the stiffness of the six axes of compliance, and 2) the location of centre-of-compliance.

According to our preliminary investigation[14], the main actuation method would be based on the FMHE's electricity-induced thermal effects so the investigation into actuation methods will not be a part of PROMOTE. However, to achieve the WP3 aim above, there are significant research and technical challenges below:

- Stiffness is difficult to measure online and thus close-loop control cannot be built directly.
- Like most polymeric composite materials, the elastic hysteresis in both tension and compression is not negligible and thus there are significant uncertainties in variables and parameters of the FMHE compliance devices[14].

We will carry out two main tasks to develop control techniques and strategies for the proposed the FMHE compliance devices.

<u>Task 3.1 Model-based control strategies (Months 13-30).</u> **Methods:** Based on the models built in Task 2.1, we will analyse model parameters to group them into i) parameters measurable directly, and (ii) parameters and variables that require indirect measurement of one or more indirect relevant variables. The WP will build on extensive previous studies on *system identification techniques*[15-17] to develop calibration techniques to adjust the parameters of the proposed FMHE devices. For i) the project will develop/integrate force/torque/tactile sensors and the associated strategies to enable the use of the sensory feedback to calibrate the proposed FMHE devices. For ii), analytic tools developed in the context of nonlinear and coupled systems will be adopted. For example, Wang's work in collaboration with M Brdys developed an algorithm that can estimate the parameters of highly nonlinear and coupled systems[18]. This approach and similar techniques have the potential to be applied to the FMHE calibration.

With calibrated models developed, we will build open-loop and closed-loop control strategies using a variety of control techniques and tools that have been established (e.g. in particular those for controlling soft robotics[19]).

<u>Task 3.2 Model-free control strategies (Months 13-30).</u> **Methods:** In addition to the control method proposed in Task 3.1, we will also adopt a reinforcement-learning-based control technique. This approach develops a self-learning mechanism to allow the controller of the proposed FMHE compliance devices to self-configure the respective control strategies through iterative interactions with physical environments.

Novelty: This work package is the first to look at the control of the FMHE compliance devices and both approaches proposed in Tasks 3.1 and 3.2 have not been developed.

Deliverable 3: Validated control techniques and strategies for the proposed FMHE compliance devices

WP 4 (addressing **O4). Prototype fabrication and demonstration** (Lead: Wang; Support: Tang) (*Months*: 1-36)

WP 4 will tie together WPs 1-3 by establishing two prototype tools (one for six-axis compliance and one for RCC) to demonstrate and communicate the potential benefits and routes to the implementation of the outputs.

<u>Task 4.1 Prototype fabrication (Months 1-30).</u> **Methods:** two types of prototype FMHE compliance devices, six-axis and RCC, will be built at the UoB using the robotic lab, cleanroom and the process room (more details about the facilities are in Section 1 Track Record).

Case for support

Task 4.2 Two case studies in partnership with industrial partners (Months 25-36). **Methods:** We will collaborate with our project partners on two case studies concerning the use of hybrid compliance in contact-rich activities (e.g. assembly and disassembly with uncertain positional errors) to identify plans to improve the performance and market value of the devices. Our provisional plan is to have two case studies in collaboration with BD and NRN. We will use the demonstration results to seek further investments from industry, and raise the TRL of the prototype tool. Our long-term vision is to commercialise the product as in a successful business model adopted by ATI or Robotiq end-effectors.

Deliverable 4 Real-world assessment results and future roadmap (Month 36)

Risk Mitigation - A risk register will be created at the start of the project and regularly updated in the quarterly project management meetings. We have preliminarily identified a small number of potential risks relating to this project. Although they are unlikely, we have measures, as outlined below, to mitigate them should they arise.

An industrial collaborator withdraws from the project. Through our network supported by MTC, SAC and NRN, we will find a replacement while our fundamental research and our demonstration activities continue.

An investigator leaves for another institution. The two investigators will still commit to this research work and deliver PROMOTE through remote collaboration. The degree of skill overlap allows temporarily cover for one another in case one of the investigators becomes unavailable before a new investigator is appointed.

Project management - The project will have quarterly internal meetings to review progress and decide corrective actions if needed. In addition, an industrial steering committee will provide strategic advice every six months. The steering committee will comprise representatives of BD, MTC, SAC, and NRN and other invited organisations.

The team will participate in six international conferences and organise two special sessions focusing on *Compliance devices for industrial automation*. The aim of attending/organising these events will be to **promote the influence of our project among three academic communities** – *industrial automation* (e.g. IEEE and IET), *sustainable production* (e.g. IMechE and CIRP), and *soft composite materials* (e.g. IMMM, ACS, MRS). High-impact learned journals will be targeted to publish the project results. Publications will include a data access statement (part of the Research Data Management plan).

All project partners will arrange non-disclosure agreements as well as having an IP register in place for **IP protection** purposes in the two case studies. We will follow Trusted Research Guidance for Academia with the support of UoB Enterprise with its extensive experience in IP protection.

We will collaborate with NRN, MTC, SAC and SmartFub to establish a network of industrial users, international academic researchers and tech-focused investors for information sharing. Two workshops will be held during the project to **showcase our research results to industry**.

References

1. Takahashi, J., *et al. IEEE/ASME Transactions on Mechatronics* 21.1 (2015): 196-204. 2. Chen, H., *et al. International Journal of Intelligent Robotics and Applications* 4.2 (2020): 149-163. **3**. Oikawa, M., *et al. IEEE Robotics and Automation Letters* 6.2 (2021): 2737-2744. **4.** Zhang, Y., *et al. Royal Society open science* 6.8 (2019): 190476. **5**. Lee, Sangcheol. *IEEE Transactions on Automation Science and Engineering* 2.2 (2005): 193-197. **6**. von Drigalski, Felix, *et al. 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020. **7.** Wang, S., *et al. IEEE Access* 7 (2019): 167534-167546. **8**. Whitney, DE. *Journal of Dynamic Systems, Measurement, and Control* 104.1 (1982): 65-77. **9**. ATI Industrial Automation, RCC Remote Compliance. Retrieved from https://www.ati-ia.com/products/compliance/compensator_product_desc.aspx. **10.** Yun, G. *et al. Nature communications* 10, no. 1 (2019): 1-9. 10. **10**. Yun, G. *et al. Matter* 3, no. 3 (2020): 824-841.**12**. Chen, F., and Wang, M. *IEEE Robotics & Automation Magazine* 27.4 (2020): 27-43. **13**. Zhang, H., *et al. IEEE/ASME Transactions on Mechatronics* 24.1 (2018): 120-131. **14**. Yun, G., *et al.* "Electro-mechano responsive elastomers with self-tuneable conductivity and stiffness*" under review, preprint available at: https://www.researchsquare.com/article/rs-2039368/v1.* **15.** Liu, Q., Ding, F., Xu, L. & Yang, E. *IET Control Theory Appl.* 13, 42–650 (2019). **16.** Massimo, M. J. *et al. IEE Proceedings D (Control Theory and Applications)* vol. 138 (1980). **17.** Kristinsson, K. & Dumont, G. A. *IEEE Trans. Syst. Man Cybern.* 22, 1033–1046 (1992). **18**. Wang, Y. *et al. Cogent Engineering* 3.1 (2016): 1173529. **19**. Wang, Jue, and Alex Chortos. *Advanced Intelligent Systems* 4.5 (2022): 2100165.

Case for support

Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)

Justification of Resources

This project is to run for 3 years and starts on the 1st July 2023. The costs included herein are 100% fEC figures.

Staff - directly incurred costs: £195,434			
Cost to Funder	**Effort**	**Staff**	**Work packages and roles**
£69,867 (Grade 7 Point 29)	100%FTE (18 months)	Research Fellow 1 (Material engineering)	A material scientist with a background in smart composite materials or a relevant topic will be recruited to work on WPs 1 and 2.
£125,567	100%FTE (32 months)	Research Fellow 2 (Mechanical engineering)	A research engineer with a background in robotics and control will be recruited to work on WPs 2, 3 and 4.

Investigators - directly allocated costs: £ 28,566			
Cost to Funder	**Effort**	**Investigator**	**Work packages and roles**
£17,412	10%FTE (3.75 hrs /wk for /36 months)	Yongjing Wang (PI)	Wang will manage the project for the entire 36 months. The PI has leading roles in WPs 2, 3 and 4, and will supervise Research Fellow 2.
£11,154	5%FTE (1.88 hrs/wk for /36 months)	Shiyang Tang (Co-I)	Tang has a leading role in WP 1, and will supervise Research Fellow 1.

Travel & Subsistence – directly incurred costs: £23,500		
Cost to Funder	**Item**	**Justifications**
£3,000	Project meetings	Project updates will be discussed with an advisory board on a six-month basis. £500 per meeting: we estimate that there will be 10 members on the board. £500 = £135 (30 Mileage/member * 10 members* 45p/mile) + £155 (£130 hotel accommodation + £25 dinner for one visitor's overnight stay) + £210 (£10.5 working lunch for 10 board members and 10 other meeting attendees, e.g RFs, PhDs). We do not expect room renting costs to be incurred at the University of Birmingham. Six meetings in total: £500*6=£3000
£16,000	Conference	Presentations at 4 international conferences and 2 virtual events for 2 people (e.g. Investigator + research fellow) Total: £2,000 per conference per person *4 conferences*2 people=£16,000 Attending virtual events will not incur travel and subsistence costs.
£4,500	Research visits	Four, 3-day visits for collaboration for 3 persons to collaborator sites (£100 accommodation and subsistence/day and £75 travel/person; £1,125 on average for each visit). Possible partner sites include but not limited to: BD, the MTC and as well as members of NRN.

Justification of Resources

<table>
<tr><th colspan="3">Consumables - directly incurred costs: £36,000</th></tr>
<tr><th>Cost to Funder</th><th>Item</th><th>Justifications</th></tr>
<tr><td>£23,000</td><td>Consumables for constructing testing jigs and control systems</td><td>The following funds are requested for this work. 6-axis force sensors (£8,000); machining consumables (£2,000); modular fixtures (£4,000); material for test rig and workstation construction (£9,000)</td></tr>
<tr><td>£9,000</td><td>Composite materials</td><td rowspan="2">Build programmable compliance components in WP1 and WP2</td></tr>
<tr><td>£4,000</td><td>Mould, PPE and fabrication tools</td></tr>
</table>

Others - directly incurred costs: £14,800		
Cost to Funder	**Item**	**Justifications**
£2,000	Recruitment	Cost of recruiting two researchers
£2,000	Support for staff relocation	Support the relocation of Research Fellows 1 and 2
£6,000	Dissemination	£3,000 for two public events involving 50 people at each event (£1500/event x 2 events); £3,000 for a dedicated project website and e-newsletters
£4,800	Facility Maintenance	Maintenance of the key facilities at the robotic lab and process rooms to be used in PROMOTE (£800 per item per year * 2 items * 3 years=£4,800) Example items: Moulding machine, robot arm and testing jigs.

Others - directly allocated costs: £15,618		
Cost to Funder	**Item**	**Justifications**
£8,356	Pool technicians (10%FTE, 3.75/hrs/wk for 24 months)	This is to provide technical support in the construction and adaptation of test equipment for WPs 2 and 3.
£7,262	Infrastructure Technician Costs	Shared staff for infrastructure support

The above costs are combined with an ***estates cost of £56,411*** and ***indirect costs £254,018*** to give a ***total project cost of £624, 347 at 100% fEC. We request EPSRC funding at 80% fEC totalling £499,477.***

NOTE: This project will benefit from the state-of-the-art sensitive robots, clean room and process room all of which are available within the school and can be used in this project for free. The total value of these robots and measurement instruments is greater than £2m.

This project will involve collaborators the MTC, SAC and Boston dynamics. They will provide an estimated in-kind contribution of approximately £60k to the project.

Boston Dynamics

July 6th, 2022

To:
Dr. Yongjing Wang
School of Engineering
University of Birmingham
Edgbaston
Birmingham
B15 2TT
United Kingdom

Dear Dr. Wang,

We are writing to confirm Boston Dynamics' strong support of the research proposal entitled "*Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)*", to be submitted for funding for consideration by the Engineering and Physical Sciences Research Council.

About Boston Dynamics: Our mission is to imagine and create exceptional robots that enrich people's lives. Building machines that can approximate the mobility, dexterity and agility of people and animals is a grand challenge. Curiosity and respect for the natural world are at the heart of our work on robots. We see products derived from this work as the next step in the human history of building machines to reduce the danger, repetition and physically difficult aspects of work. One of the things that makes Boston Dynamics globally unique is the ambition to build dynamically stable, legged machines.

We are excited to have the opportunity to participate in this University of Birmingham led project and thereby happy to confirm **Boston Dynamics'** willingness to support the project. The proposed research is well aligned with Boston Dynamics's continued focus on innovation in automation, and also with our goal to take robotics and autonomous systems into unstructured environments. This proposal on novel compliance devices for robotic assembly and disassembly is of considerable interest to many production, testing, inspection and repair and maintenance applications that are valuable applications of legged robots.

Over the duration of the project we anticipate providing in-kind contributions. Our in-kind contributions will be focused on supporting the specification of robot solutions, specifically technical and engineering support for the integration of your solutions with Boston Dynamics' SPOT robot platform. To further demonstrate our commitment to this project, we will plan on regularly meeting Dr Wang to discuss the development of the project (every 6 months).

We hereby wish to express our strongest support and look forward to seeing our robots being part of the exciting technical solutions and products to be developed within this project.

Yours sincerely,

DocuSigned by:
Ed Colp
B759023CA40A450...

Ed Colp
Sales Manager, Academia and Research
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Dr Yongjing Wang
School of Engineering
College of Engineering and Physical Sciences
The University of Birmingham
Edgbaston
Birmingham
B15 2TT

14th July 2022

Dear Dr Wang,

Support for the EPSRC proposal

Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)

I am writing to confirm the MTC's support for your application to the EPSRC.

The MTC is part of the High Value Manufacturing Catapult (HVMC). The HVMC is the catalyst for the future growth and success of advanced manufacturing in the UK with the purpose of collaborating with academia and companies of all sizes to bridge the TRL gap between technological concepts to commercialisation. The HVMC offers access to leading edge equipment, expertise, and an environment for industry collaboration.

The MTC's mission is to generate rapid and sustainable industrial growth in the UK by delivering novel manufacturing system solutions for customers, large and small, across sectors as diverse as automotive, aerospace, rail, informatics, food & drink, construction/civil engineering, electronics, oil & gas and defence. Partnership and collaboration is fundamental to our operations through which we develop and prove innovative manufacturing processes and technologies in an agile, low risk environment, in partnership with industry, academia and other institutions.

The MTC and the University of Birmingham have developed a strong partnership over many years, in particular through Birmingham's status as a founder member of MTC, which began over a decade ago. Since then we have enjoyed successful collaborations on a range of projects, including AUTOREMAN and ATARI within the disassembly and remanufacturing domains. The proposed research is well aligned with the MTC's continued focus on innovation in automation, and with the wider High Value Manufacturing Catapult's focus in sustainability and remanufacturing.

Therefore, we are supportive of your proposal and would like to engage with you and the team at the University of Birmingham. We propose the following mechanisms of engagement:

- Regularly meeting the research team to discuss the development of the project

  (every 6 months)
- Access for the project to MTC's workshop facilities and support from the MTC's technology teams
- Supporting the exploitation of the research with potential end users
- Potential to integrate project results into a physical demonstrator at the MTC facilities to promote wider dissemination and engagement with industry
- Exploring the development of new collaborative projects.

The estimated in-kind value of this support will be around £30K over the 3-year term of the project.

We look forward to supporting and participating in this exciting program of research.

Yours sincerely,

Helen Finch

Dr. Helen Finch

Associate Director – Academic Engagement

Satellite Applications Catapult

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Dr Yongjing Wang
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College of Engineering and Physical Sciences
The University of Birmingham
Edgbaston, Birmingham
B15 2TT

CATAPULT

08th August 2022

Dear Dr Wang,

Re: Letter of support for the EPSRC proposal "Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)"

On behalf of Satellite Applications Catapult, we are delighted to provide our strongest support to the above-mentioned EPSRC grant proposal which aims to develop new methods that combine passive and active compliance to create hybrid compliance that can deliver high efficiency as well as high flexibility for robotic systems.

Robotic manipulation in space is a critical capability for the future commercial exploitation of space, but several important scientific challenges must be first addressed. This research is timely because the UK aspires to become a dominant player in space and collaboration with academia is essential to achieve this aim. For example, given the significant launch costs, there is an increasing desire for in-orbit servicing, assembly and manufacturing of space infrastructure. Robotic arms on space vehicles do not have the luxury of being mounted on a fixed platform and hence the manipulation of often uncertain space payloads, which could be large, massive, and flexible, causes significant dynamic interaction between robot and payload. The PROMOTE programme addresses these problems with its approach to hybrid compliance during grasping and manipulation.

The Satellite Applications Catapult is an independent innovation and technology company, created to foster growth across the economy through the exploitation of space technologies. We help organisations make use of and benefit from satellite technologies and bring together multi-disciplinary teams to generate ideas and solutions in an open innovation environment. We deliver our activities through defined programmes of work focussed on market opportunities.

In view of our strong interest in this project, Satellite Applications Catapult will gladly support the PROMOTE programme, subject to it being funded by the ESPRC, by:

- Regularly meeting the research team to discuss the development of the project twice-a-year over the 3-year project duration and providing high-level advice as needed (£ 1,650 over three years)

- Giving PROMOTE researchers access to our In-Orbit Service & Manufacturing validation and verification facility which includes a 6-DOF floating platform to emulate manipulation of payloads in space and supporting digital infrastructure subject to need and availability at the time (£ 14,350 over three years)

- Hosting PROMOTE academic visits and researcher secondments to work on our facilities, collect data, try new algorithms and collaborate with our engineers subject to availability and where commercial confidentiality allows, providing data for technique development (£ 4,350 over three years)

- Attending workshops and industrial showcase events that demonstrate PROMOTE research, aiding with public exposure of PROMOTE research, advising on pathways to potential impact and aiding with hosting some industrial workshops (£ 1,650 over three years)

The above in-kind support is estimated to be worth £ 22,000 over the 3-year project duration.

We hope this project gets funded as we look forward to working with the PROMOTE team.

Yours sincerely,

Paul Febvre

Chief Technology Officer
Satellite Applications Catapult

National Robotics Network

Dr. Yongjing Wang
School of Engineering
College of Engineering and Physical Sciences
The University of Birmingham
Edgbaston,
Birmingham,
B15 2TT

Kevin Blacktop
Chair – National Robotics Network
Email – Kevin.Blacktop@sky.com
Mobile - 07494 874931
www.nationalroboticsnetwork.org

6/7/21

Dear Dr Wang,

I am very happy to write this statement in support of your application to the EPSRC on '**Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)**'.

The National Robotics Network (NRN) is an open network of industry and academic professionals from across the UK interested in robotics and autonomous systems. Building on the recent UK strategy for Robotics and Autonomous Systems, RAS2020, the NRN is identifying ways in which the UK RAI community, can help drive the future of robotics in the UK through world class research, cutting edge companies and innovative application.

Taking robotics and autonomous systems out from the factories and into unstructured environments will unlock the significant productivity and safety improvements that are desperately required by many industries from utilities, transport networks and other infrastructure industries. One of the major problems for robotics and autonomous systems is making them adaptable to changing environmental conditions and for variability both in the tasks to be undertaken and the materials and components they will work with.

We believe the proposed EPSRC proposal will provide valuable R&D and Proof of Principle provision for the UK industry. Your proposal on end-effector tools for robotic assembly and disassembly is of considerable interest to many production, testing, inspection and repair and maintenance businesses.

Therefore we are supportive of your proposal and would like to actively engage with you and the team. We propose the following mechanisms of engagement.

- Supporting the exploitation of the research with potential end uses,
- Regularly meeting Dr Wang to discuss the development of the project (every 6 months),
- Exploring the development of new collaborative projects.

Finally, we wish you all success with your application and hope to work together in the near future.

Yours sincerely,

K. Blacktop

Kevin Blacktop

UNIVERSITY OF BIRMINGHAM

School of Engineering

Professor Karl Dearn
Deputy Head of School of Engineering
Head of Department of Mechanical Engineering

5th September 2022

EPSRC, Polaris House
North Star Avenue
Swindon, SN2 1ET

RE:Hybrid compliance: programmable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (PROMOTE)

Dear Sir/Madam,

I am delighted to be able to write in support of the above research proposal. The Department of Mechanical Engineering, School of Engineering, will host the work to be carried out in this proposal. Should the grant be awarded, the School will provide all the necessary research and administrative support that the project requires.

The PI of the project, Dr Wang, is an EPSRC NIA recipient and holds other research grants that have enabled him to gain experience managing resources. With the support from Co-Is and the University's Research Support Services, he will have plenty of support to manage the resources for the project. The University also enrols all early career staff in a comprehensive training and support program to enable them to reach excellence, for which Dr Wang is registered.

Robotics and autonomous processes are strategically important research areas for the School of Engineering and the formation of a University Institute of Robotics. To support this aspiration and Dr Wang's proposed research, the School has made several high-profile appointments, including Professor Samia Nefti-Mezzani OBE.

The research team will have full access to all the necessary laboratory facilities to undertake the research proposal. In addition, the research team will be based at the new £65M School of Engineering Building which opened to staff in April 2021, and it also houses all the necessary administrative support for the project.

Finally, I would like to wish the very best with this application; I sincerely hope that it is successful in receiving funding.

Yours faithfully,

Professor Karl Dearn

Edgbaston, Birmingham,
B15 2TT, United Kingdom
www.birmingham.ac.uk

Tunable six-axis remote compliance enabled by smart hybrid filler elastomers for robotic assembly and disassembly (REMOTE)– Work Plan

The academic team comprises two investigators (Wang and Tang) and two full-time researchers (RF1 and RF2).

	Months 1-6	Months 7-12	Months 13-18	Months 19-24	Months 25-30	Months 31-36
WP 1. FMHE shear pads (Tang, Wang, RF1)	D1.1		D1.2			
Task 1.1 Investigating into the shear properties of FMHE						
Task 1.2 New design of shear pads using FMHE						
Task 1.3 Fabrication and validation of FMHE shear pads						
WP 2. FMHE compliance devices (Wang, Tang, RF1, RF2)				D2		
Task 2.1 Design and modelling of hybrid compliance with tuneable stiffness and centre-of-compliance						
Task 2.2 Fabrication and validation of hybrid compliance with tuneable stiffness and centre-of-compliance.						
WP 3. Control techniques and strategies (Wang, Tang, RF2)					D3	
Task 3.1 Model-based control strategies						
Task 3.2 Model-free control strategies						
WP 4. Prototype fabrication and demonstration (Wang, Tang, RF1, RF2)						D4
Task 4.1 Prototype fabrication						
Task 4.2 Two case studies in partnership with industrial partners†						
Project management (Wang)						
Advisory meetings	*	*	*	*	*	*
Present at six international conferences†		*		*		*
Organise two workshops to engage industry			*			*

†Videos will be published

<u>Deliverables</u>

D1.1: The mechanical performance of the FMHE as compliance materials

D1.2: Fabricated FMHE shear pads

D2: Validated compliance devices (i.e. two types: six-axis and RCC) with tuneable stiffness and centre-of-compliance

D3: Validated control techniques and strategies for the proposed FMHE compliance devices

D4 Real-world assessment results and future roadmap

workplan