Final report for projects funded by the Leibniz Association's Competition Procedures

Project title: MUSIGAND - Multiscale Modeling and Engineering Simulation of Next Generation Multifunctional Adhesives for Handling Applications

Project number: K279/2019

Executive Summary

The MUSIGAND project is an international collaboration focused on the mechanisms of advanced bioinspired handling devices and ensuring their reliability through a combined approach of theoretical simulation and experimental validation. The project has achieved remarkable success in meeting its objectives and milestones, thanks to extensive cooperation between INM and Saarland University and the input from international collaborators. While the collaboration with Santa Barbara went smoothly due to prior joint work, the communication with other international partners, including new contacts, was affected by the restrictions imposed by the COVID-19 pandemic. However, by predominantly using virtual methods for internal group interactions and international cooperation, the project managed to overcome these limitations and succeeded in meeting all objectives.

To date, the project has resulted in the publication of 12 international papers and the filing of 1 patent. A notable achievement is the successful integration of machine learning techniques to enhance the reliability of gripping using the new technology. Through a combination of simulation and experimentation, innovative devices have been developed to tackle the challenges associated with handling micro-objects. The collaboration with theoretical experts has improved the understanding of the contact processes in micropatterned structures and has provided a valuable platform for bridging the gap between fundamental solutions and practical handling requirements.

The most significant break-through lies in the first-time implementation of artificial intelligence and machine learning to the handling with bioinspired microstructures. The project maintained close ties with practical applications, ensuring a smooth transfer of new findings into the design of novel handling materials and their application in demanding handling processes. This demonstrates how considerations from basic scientific research can influence and expedite the practical implementation of solutions in real-world applications.

1. Achievement of objectives and milestones

Adhesion to roughness: Largely through the PhD thesis of Christian Müller, advised by Prof. Martin Müser (Saarland University), the Milestones 1 and 3 were fully achieved; for Milestone 2, first results are available that can be extended to real pick-and-place processes.

Controlled release: Through work performed by Dr. Xuan Zhang, all 3 Milestones were achieved (see below).

Contact signatures: The PhD thesis of Manar Samri succeeded in achieving the objectives of Milestones 1 and 3 were fully achieved; Milestone 2 (rough contacts) proved more difficult and first relevant observations were made.

The elements of the final objectives were in total fulfilled. Topography effects are now much better understood, the handling of difficult objects has made big advances, and the use of contact signatures for real-time performance prediction, which was pioneered in this project, is on the verge of practical implementation.

The financial statement reflects largely the original financial planning. One exception was the interruption by the COVID-19 pandemic, which delayed international workshops and cooperation. The project duration was therefore extended at the original cost by six months to June 30, 2023.

2. Activities and obstacles

As intended, the project partners, INM and Saarland University, worked closely together and successfully achieved their goals, particularly reaching Milestones WP 1 and 3 mentioned earlier. The collaboration with the University of California was also executed efficiently, resulting in the development of innovative designs for active handling microstructures, as outlined in WP 2. An additional collaboration with UC San Diego led to first insights on the dynamic behavior or our gripping systems intended for space applications.

Due to the pandemic, the planned workshops had to be postponed. In addition to numerous virtual meetings, two collaborative and international workshops were organized: In October 2022, a workshop was hosted by the cooperation partner University of California in Santa Barbara to discuss and disseminate the results among leading colleagues. In February 2023, we organized a scientific workshop at INM in Saarbrücken. Through international cooperation and synergy, the understanding of bioinspired handling processes was significantly advanced.

3. Results and successes

A major review article was published in the leading review journal:

This paper reviews the fundamental interaction mechanisms of such micropatterns with liquids, solids, and soft matter such as skin for control of wetting, self-cleaning, anti-fouling, adhesion, skin adherence, and sensing.
E. Arzt, H. Quan, R.M. McMeeking, R. Hensel, Progress in Materials Science 119 (2021) 100778

Adhesion was successfully optimized, with increasing understanding for rough surfaces:

A study investigated the impact of cap geometry on enhancing the dry adhesion of micropatterned polymeric surfaces. The study established the effect of stalk diameter and Young's modulus on adhesive force, leading to an optimal design for mushroom-shaped fibrils.
X. Zhang, Y. Wang, R. Hensel, E. Arzt, *Journal of Applied Mechanics*, 88 (2021) 031015

In another study, we propose a cupped microstructure with a cavity inspired by suction organs found in aquatic animals, addressing the challenge of underwater or wet adhesion. This novel microarchitecture shows promise for future applications on real, rough surfaces under wet conditions.
Y. Wang, R. Hensel, *Advanced Functional Materia*ls, (2021) 2101787

Contact aging was found to enhance adhesion of micropatterned silicone. Adhesion increase varies across the microarray due to local conditions, but overall, adhesion of entire specimens follows similar power laws determined by mean contact aging of individual structures. Contact aging should be considered for long-term fixations and chemically attractive material combinations.
J. Thiemecke, and R. Hensel, *Advanced Functional Materials* 30(50) (2020): 2005826

Subsurface microstructures affected adhesion of highly confined elastic films. Plane strain simulations reveal interfacial stress distributions and characteristic adhesion failures. While the micropatterned subsurface affects contact stiffness, stress distribution, and detachment behavior, the adhesion performance only shows slight improvement compared to a non-patterned subsurface.
M. Samri, A. Kossa, and R. Hensel, *Journal of Applied Mechanics* 88.3 (2021): 031009

In a combined theoretical and experimental study, the coaction of viscous and multistability hysteresis was revealed in an adhesive, nominally flat punch. We compare the simulated and experimentally measured time evolution of the interfacial force and the real contact area between a soft elastomer and a rigid, flat punch, to which small-scale, single-sinusoidal roughness is added. A coaction of viscous- and multistability effects is expected to occur in macroscopic polymer contacts and to be relevant, e.g., for pressure-sensitive adhesives and modern adhesive gripping devices.
C. Müller, M. Samri, R. Hensel, E. Arzt, M. Müser, *Journal of the Mechanics and Physics of Solids.* 174 (2023): 105260

- **Controlling release, especially for small objects:**

  Inspired by the trigger plant, we explored a mechanical metastructure for overcoming adhesion involving a snap-action mechanism. With an unprecedented switching ratio (between high and low adhesion) exceeding 10^4, this concept proposes an efficient paradigm for handling and placing superlight objects.
  X. Zhang, Y. Wang, Z. Tian, M. Samri, K. Moh, R. M. McMeeking, R. Hensel, E. Arzt, *Science Advances* 46.8 (2022): eadd4768

  Another set of experiments demonstrated that the release from a smooth surface involves sliding of the contact during compression and subsequent peeling of the object during retraction. As a result, an expression for the pull-off force is proposed as a function of the sliding distance and a guide to an optimized design for these release structures is provided.
  Y. Wang, X. Zhang, R. Hensel, E Arzt, *Advanced Materials Interfaces* (2022): 2101764

  In another work, new microfibrillar designs are reported exhibiting directional buckling with high switching ratios in the order of 20. Their functionality is illustrated by in situ optical observation of the contact signatures. Such micropatterns can enable the successful release of small objects with high placement accuracy.
  L. Barnefske, F. Rundel, K. Moh, R. Hensel, X. Zhang, E. Arzt *Advanced Materials Interfaces* 33.9 (2022): 2201232.

- **Contact signatures and statistical effects:**

  Catastrophic failure of microfibrillar adhesives can be avoided in compliant systems based on statistical analysis of adhesive strength. We explore the importance of statistical properties in attachment stability and propose a stability criterion based on Weibull parameters, considering the compliance of the loading system. Experimental results align with the theoretical stability map, demonstrating a transition to unstable detachment at low system stiffness. This informs gripper design and prevents catastrophic failure in adhesive handling applications.
  R. Hensel, J. Thiemecke, J. A. Booth, *ACS Applied Materials & Interfaces* 13(16) (2021): 19422-19429.

  Another study introduces a statistical model that captures the distribution of local adhesive strength and its impact on micropatterned adhesive performance. The model improves our

understanding of real-world adhesive behavior, including the prediction of unstable detachments in compliant systems.
J. A. Booth and R. Hensel, *Applied Physics Letters* 119.23 (2021): 230502.

First dynamic tests were performed to test the impact of our gripping microstructures with hard objects, as a simulation of capturing uncooperative objects floating in orbit as space debris. Contact signatures were recorded with a high-speed camera to correlate microscopic impact absorption with gripping behavior. First theoretical models incorporating the dynamics were developed to delineate the regions of successful gripping performance. (collaboration with University of California San Diego, in preparation)

- **Predicting the adhesion strength and handling by machine learning:**

  We present an in-line monitoring system that allows optical analysis of an array of individual fibrils in contact with a smooth glass substrate, followed by the prediction of their adhesion performance through machine learning. Support vector regression and boosted tree models exhibited highest accuracies and outperformed an analytical model reported in literature. Overall, this new approach enables predictions in gripping objects by contact observations in near real-time.
  M. Samri, J. Thiemecke, E. Prinz, R. Hensel and E. Arzt, *Materials Today* 53 (2022): 41

  Machine learning was applied to object manipulation with bio-inspired microstructures. We propose an in-situ optical monitoring system of the contact signatures, coupled with image processing and machine learning. The system allowed an assessment of the picking process for objects of various mass. Several classifiers showed a high accuracy of about 90% for successful prediction of attachment, depending on the mass of the object. The results promise improved reliability of handling objects, even in difficult situations.
  M. Samri, J. Thiemecke, R. Hensel, E. Arzt, in review

- **Transfer activities:**

  A new ERC Proof-of-Concept project was started and completed (“Stick2See”). The objective of this European project was to assess the market potential of attachment devices that incorporate optical sensing for enhanced handling reliability.The content highlights the need for new handling concepts in automation technology, particularly in the manipulation of extremely small objects. This solution has significant economic potential in the multi-billion Euro market of automated micro assembly, particularly in Europe where leading automation companies are located.

  A new photoresist was developed and patented for advanced microstructures. The invention involves a curable composition for direct printing of elastic and complex microstructures using two-photon lithography. Our composition enables the fabrication of complex micron-sized structures with high printing accuracy, tunable Young's modulus, deformability, and adhesion. (Z. Tian, X. Zhang, R. Hensel, E. Arzt, patent filed)

  A newly developed optical gripper was provided to a spin-off company for assessment. Based on the project's findings, a novel gripping system incorporating optical monitoring has been developed. Currently, our partner company is conducting tests to assess the gripper's market viability.

  First demonstration of a micropatterned adhesive on the International Space Station:
  The micropatterned adhesives, which were developed and fabricated in our laboratory, underwent rigorous testing by NASA aboard the International Space Station (ISS). These adhesives were specifically designed for gripping satellite components in outer space. The tests were successful and demonstrated the docking capabilities of two microbots under low-gravity conditions.

4. Equal opportunities, career development and internationalisation

The project demonstrates a significant commitment to equal opportunity. The principal investigator has made dedicated efforts to ensure equal opportunities for all applicants within the project's framework. As a result, the research group showcases strong representation of female scientists. Among the two PhD students hired for the project, one is a female. Similarly, among the two postdocs, one was female (and received a Humboldt Young Scientist Award). Recognizing the success of the female postdoc, the PI has appointed her as the deputy group leader at the beginning of 2022.

5. Structures and collaboration

The planned collaboration structure was active and successful. The daily interaction with Saarland University, as initially planned with Müser, Sukhomlinov and Müller, was fully operational. Additionally, the collaboration with Santa Barbara, led by McMeeking, was active as scheduled. However, due to the pandemic, the planning for the workshops, which were an integral part of our project, had to be substantially revised. To compensate for this, we organized a comprehensive international workshop in October 2022 at the University of California in Santa Barbara (report enclosed).

6. Quality assurance

This project has implemented all the required quality assurance measures. Adherence to INM's standards, which align with DFG regulations, ensures good scientific practice (INM standards have recently received formal approval from DFG). In line with this, preference was given to open access publications rather than subscription access. Animal testing was not conducted.

7. Additional resources

The MUSIGAND project held a central position within the expertise and experience of the Functional Microstructures group led by the PI. It hence benefitted from its integration into a vibrant research environment and fostered close collaboration with other activities and projects. Of particular significance is the ERC Proof of Concept project “Stick2See”, marking the third PoC project acquired by the PI focused on gecko-inspired adhesive technology. Furthermore, the association with a company proved mutually beneficial, broadening the participants' horizons to explore potential applied and commercial aspects. The institute has estimated an annual contribution of approximately 200,000 Euros in in-kind resources for personnel, along with an additional 50,000 Euros allocated for consumables.

8. Outlook

This project was the first worldwide successful activity combining theory, simulation and experiment to create predictive reliability of the new bioinspired paradigm of handling objects with micropatterned switchable adhesives. Despite the pandemic, the project successfully completed virtually all tasks in accordance with the proposed objectives. For the first time, real-time optical monitoring of contact signatures through the gripping structures was demonstrated. Topography effects, simulation and implementation of the release of challenging objects, comprehensive comprehension of contact signatures, and predictive calculations of real-time performance are now much better understood. The results of this project are thus relevant in the academic field and will very likely accelerate the future industrial implementation of this new technology.