Lehrstuhl für
Technische Dynamik
Prof. Dr.-Ing. habil. Sigrid Leyendecker

Report
Institute of Applied Dynamics
2024

Friedrich-Alexander-Universität
Technische Fakultät

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Contents

1 Preface

Welcome to a brief look at the 2024 scientific and teaching activities of the Institute of Applied Dynamics (LTD) at Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). Our work integrates simulation and optimal control of the dynamics of multibody systems in biomechanics and robotics. Our core subjects are:

- **biomechanics**
- **motion capturing**
- **structure preserving simulation and optimal control**
- **multibody dynamics and robotics**

For example, we perform heart simulations and model muscle function, blending electrical stimuli and mechanical deformation. Furthermore, we study the mechanics of human motion, like grasping, shoulder movement, walking. On this behalf, our motion capturing lab helps us combine theoretical models with real-world experiments. This integration enables us to optimise control strategies across various scales. Moreover, we work on developing numerical methods for dynamic simulation and optimal control, using approaches like variational integrators and Lie group methods to tackle challenges in multibody dynamics, robotics and fracture mechanics.

Many thanks to our technical, scientific and administrative staff at LTD, and also to all the students involved to make it a successful year at the Institute of Applied Dynamics. We wish you an enjoyable time glancing through our annual report.

2 Team

head of institute
Prof. Dr.-Ing. habil. Sigrid Leyendecker

team assistant
M.A. Ruby Chen

technical staff
M.Sc. Elisa Fleischmann
M.Sc. Markus Lohmayer

akademischer Rat
Dr.-Ing. Giuseppe Capobianco, Akad. Rat

postdoc

Dr.-Ing. Xiyu Chen	
Dr.-Ing. David Holz	until 15.07.2024
Dr. rer. nat. Michael Konopik	
Dr.-Ing. Denisa Martonová	
Dr. Rodrigo Sato Martín de Almagro	

scientific staff

M.Sc. Gamal Amer	from 01.12.2024
M.Sc. Birte Coppers	
M.Sc. Simon Heinrich	
M.Sc. Deepak Balasaheb Jadhav	
M.Sc. Eduard Sebastian Scheiterer	until 30.04.2024
M.Sc. Prateek Prateek	from 01.10.2024
M.Sc. Martina Stavole	until 30.09.2024

students
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Amelie Daum
Vijayan Sheela Devadas
Vamshidar Enugala
Melanie Fuchs
Chen Jiaan
Maalon Jochmann
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Alex Klitzen
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Suthan Lemaire
Aaron Linsel
Fangxi Liu
Onkar Marathe
Hasmik Mikayelyan
Amir Mohammadi
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Amir Pour Mohammadi
Prateek Prateek
Aswin Ramachandran
Venkatesan Rishyavandhan
Poojary Saurabh
Tim Seeberger
Prashanth Setty
Amit Sharma
Hetali Tambe
Tran Tan
Aastha Tapaliya
Sathiya Varadhan
Jiyai Wang

Student assistants are mainly active as tutors for young students in basic and advanced lectures at the Bachelor and Master level. Their contribution to high quality teaching is indispensable, thus financial support from various funding sources is gratefully acknowledged.


G. Amer


G. Capobianco


R. Chen


X. Chen


B. Coppers


E. Fleischmann


S. Heinrich


D. Holz


D. Jadhav


M. Konopik


M. Lohmayer


D. Martonová


P. Prateek


R.T. Sato


E.S. Scheiterer


M. Stavole


S. Leyendecker

3 Research

3.1 ETN – THREAD

As of March 31, 2024, the THREAD project has officially concluded, marking a successful milestone in the study of highly flexible slender structures essential to high-performance engineering systems. This European Training Network (ETN) initiative, part of the Marie Skłodowska-Curie Programme under Horizon 2020, was coordinated by Prof. Dr. Martin Arnold from the Institute of Mathematics at Martin Luther University Halle-Wittenberg, with Prof. Dr.-Ing. habil. Sigrid Leyendecker as principal investigator and work package leader. Throughout its duration, the project achieved significant progress in mechanical modeling, mathematical formulations, and the development of numerical methods for structures such as yarns, cables, and hoses.

The scientific output of THREAD is substantial, with 26 publications in high-quality international journals and 14 additional papers under review. A standout contributor to this success was our fellow LTD Early Stage Researcher (ESR10), Martina Stavole, who joined the project in 2020 and had a successful doctoral defense in December this year. She executed a series of secondments: testing endoscopes under bending and torsion at ITWM Fraunhofer in Kaiserslautern, solving beam contact problems in Liège, and conducting quasi-static analyses using Neural Networks at NTNU in Trondheim, as well an industrial secondment at Karl Storz Endoscopes in Estonia.

We extend our heartfelt thanks to all participants for their dedication and collaboration throughout this project. For more information, please visit: https://thread-etn.eu

3.2 SFB 1483 – EmpkinS

In 2024, the Collaborative Research Center SFB 1483 "Empatho-Kinaesthetic Sensor Technology" (EmpkinS) continued its efforts to advance the development of sensor technology and the collection of movement data to better understand human body dynamics. Spearheaded by Prof. Dr. Martin Vossiek and Prof. Dr. Björn Eskofier, the project aims to integrate external movement observations with internal biomedical processes to capture and monitor body functions non-invasively.

The subprojects C04 and D01 are making significant progress toward these goals. Led by Prof. Dr.-Ing. habil. Sigrid Leyendecker at the Institute of Applied Dynamics and PD. Dr. habil. Anna-Maria Liphardt at the Department of Internal Medicine 3, FAU & Universitätsklinikum Erlangen, efforts are moving into a phase where initial results are being presented. Doctoral candidates M.Sc. Simon Heinrich and M.Sc. Birte Coppers are the key players in achieving these milestones, culminating in the development of several journal publications. These subprojects have also fostered substantial collaborations between institutes and universities, including the Queensland University of Technology (QUT) and University Jaume I, Castelló de la Plana, Spain, highlighting the project's international reach and multi-disciplinary approach.

Throughout the year, regular meetings have provided platforms for planning and discussing progress, allowing researchers to align their efforts and set the stage for future achievements. The insights and data collected are paving the way for innovations in sensor technology. For more information about the project's developments, please visit https://www.empkins.de.

3.3 FRASCAL – Fracture across Scales

The DFG Research Training Group (RTG) FRASCAL – Fracture across Scales (GRK 2423) is a multidisciplinary research initiative comprising 12 projects. Among these, Project P9 is being conducted at LTD under the supervision of Prof. Dr.-Ing. habil. Sigrid Leyendecker. During the first cohort of FRASCAL, Dr.-Ing. Dhananjay Phansalkar developed a variation-based, spatially adaptive phase-field model for fracture. Building on this foundation, in the second cohort M.Sc. Deepak B. Jadhav has developed a modified asynchronous variational integrator (AVI) for phase-field modeling of dynamic fracture. He is currently working on incorporating temporal adaptivity into the previously developed spatially adaptive model using a newly devised AVI for dynamic phase field fracture. In October 2024, M.Sc. Prateek Prateek joined the third cohort of FRASCAL and will focus on variational integrators and peridynamics to study dynamic fracture. This research is being carried out in close collaboration with the RTG's Mercator fellow, Prof. Dr. Michael Ortiz, and Prof. Dr.-Ing. Kerstin Weinberg.

The Recruitment Symposium for the RTG was held on September 18, 2024. Doctoral candidates from the second cohort had the opportunity to meet prospective doctoral candidates for the third cohort, leading to many interesting discussions. Additionally, the RTG organized a FRASCAL seminar on October 25, 2024. During the seminar, various research groups presented the progress of their work to date. The question-and-answer sessions following the presentations were particularly valuable, as they included insightful questions posed by the supervisors from different groups.

Images by: Ann-Sophie Herzner

3.4 Heart project

The heart project is focusing on the modelling of the cardiac function to better understand cardiovascular disease, to be able to early detect or even predict heart failure and develop adequate patient specific therapies and medical devices. We are currently working on a rat as well as a human heart model. Recently, thanks to the constitutive neural network approach, we were able to discover accurate material model for passive human myocardium. We are also currently working on a dynamic, viscoelastic, electromechanical shell model to develop an artificial heart muscle to support the cardiac cycle in case of disease.

3.5 Symplectic discretization for optimal control problems in mechanics

The DFG project LE1841/12-1 aims at deriving and characterizing a new approach to solving optimal control problems for mechanical systems. This is a joint project between the Institute of Applied Dynamics at FAU and the Numerical Mathematics and Control research group at the Universität Paderborn. After deriving said new approach by defining a new control Lagrangian, the next steps have been focused on discretising the theory, analyzing this discrete setting vs. the continuous setting and deriving variational integrators from these. Also, the geometry of the continuous procedure and further generalizations have been studied. Dr. Michael Konopik is focusing on the discrete setting, while Dr. Rodrigo T. Sato Martín de Almagro and Dr. Sofya Maslovskaya are focusing on generalization of the new approach on the continuous setting.

3.6 Scientific reports

The subsequent pages present a brief overview on the current research projects pursued at the Institute of Applied Dynamics. These are partly financed by third-party funding German Research Foundation (DFG) in addition by the core support of the university.

Research topics

Optimal control of a pendulum with set-valued friction
Giuseppe Capobianco, Sigrid Leyendecker

Muscle path modeling based on the geodesic function for shoulder model
Xiyu Chen, Maxence Lavaill, Simon Heinrich, Sigrid Leyendecker

Evaluation and perspectives of using marker-based motion capturing to characterize hand movements in patients with rheumatic diseases
Birte Coppers, Simon Heinrich, Verónica Gracia-Ibáñez, Néstor Jarque-Bou, Sara Bayat, Georg Schett, Sigrid Leyendecker, Anna-Maria Liphardt

Robust muscle path modelling for arbitrary movements
Simon Heinrich, Xiyu Chen, Saulo Martelli, Peter Pivonka, Sigrid Leyendecker, Maxence Lavaill

A modified asynchronous variational integrator for phase field modeling of dynamic fracture
Deepak Jadhav, Dhananjay Phansalkar, Kerstin Weinberg, Michael Ortiz, Sigrid Leyendecker

Analysis of discrete Lagrangians defined for a new augmented approach to optimal control problems in mechanics
Michael Konopik, Rodrigo T. Sato Martín de Almagro, Sofya Maslovskaya, Sina Ober-Blöbaum, Sigrid Leyendecker

Constitutive neural networks – automated model discovery for human cardiac tissue
Denisa Martonová, Mathias Peirlinck, Kevin Linka, Gerhard A. Holzapfel, Sigrid Leyendecker, Ellen Kuhl

Structure preserving integrators for fracture simulations using peridynamics
Prateek Prateek, Giuseppe Capobianco, Sigrid Leyendecker

High order variational integrators for continuum mechanics, constrained mechanical systems and optimal control
Rodrigo T. Sato Martín de Almagro, Sigrid Leyendecker

Optimal control of a pendulum with set-valued friction

Giuseppe Capobianco, Sigrid Leyendecker

For many engineering applications, friction is vital for their functionality. E.g. for walking and driving, the friction with the ground is exploited for locomotion. The goal of this project is to explore the optimal control of mechanical systems with friction. To do so, as a benchmark problem, we analyze a pendulum driven via a frictional coupling, which exerts a moment M on the pendulum. The moment is due to friction and therefore depends on the difference between the angular velocity of the pendulum $\dot{\varphi}$ and the angular velocity of the driving shaft ω, which is the control input of the system.

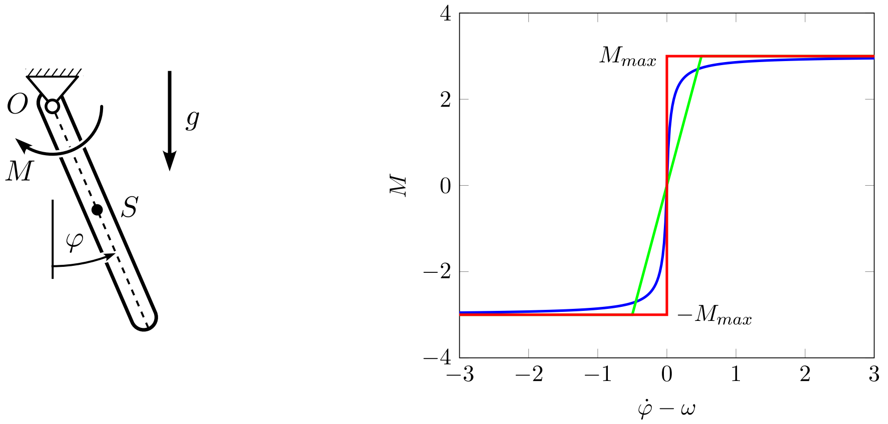


Figure 1: Left: pendulum driven by moment M. Right: Coulomb friction – (red) set-valued, (green) C^0-regularization and (blue) smooth regularization.

To find an upswing trajectory, we solve the optimal control problem of searching the input ω such that starting at rest for $\varphi(0) = 0$, the pendulum swings up to $\varphi(T) = \pi/2$ with $\dot{\varphi}(T) = 0$ and minimizes the cost functional

$$C(\omega) = \frac{1}{2} \int_0^T \omega^2 \mathrm{d}t \, .$$

For the three friction laws shown in Figure 1, an upswing trajectory for $T = 4$ found using the Discrete Mechanics and Optimal Control approach is shown in Figure 2, respectively.

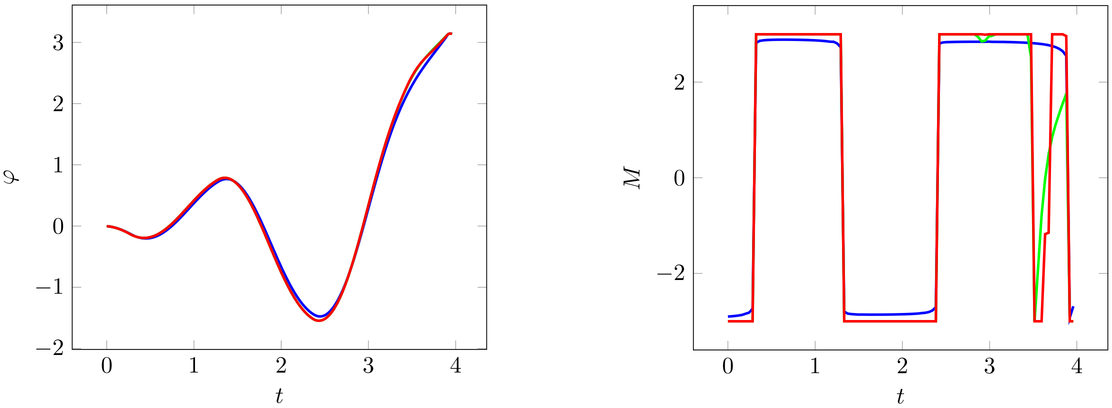


Figure 2: Upswing trajectories with friction law: (red) set-valued, (green) C^0-regularization and (blue) smooth regularization.

The presented results look very promising, however, the convergence behavior of the used method is very parameter sensitive. This stems from the fact that conventional optimization algorithms can barely handle the nonsmooth constraints induced by the friction law. The above results show the need for novel solution strategies, which shall be developed in this project.

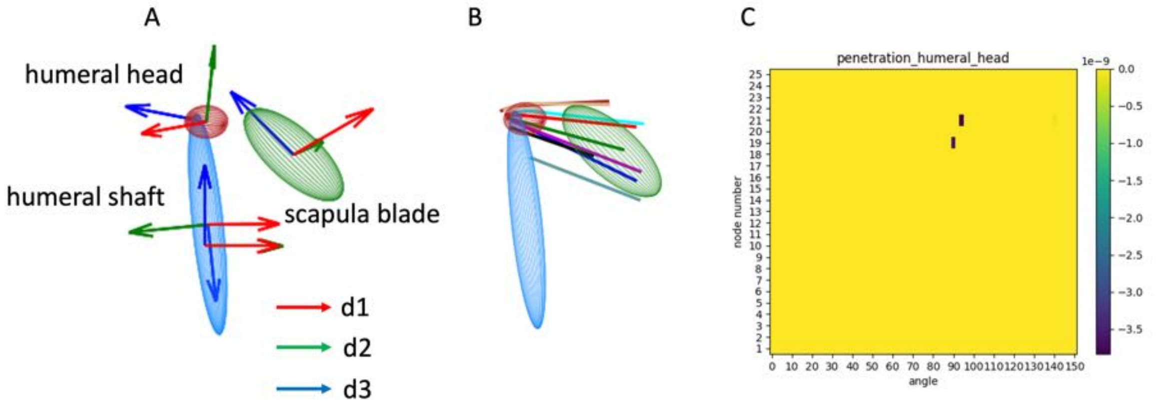
Muscle path modeling based on geodesics for a shoulder model

Xiyu Chen, Maxence Lavaill[12], Simon Heinrich, Sigrid Leyendecker

Biomechanics explores the mechanical behavior of biological tissues and musculoskeletal systems. Using Riemannian geometry, geodesic curves—defined by zero geodesic curvature-serve as optimal paths dictated by the surface curvature. This study employs discrete geodesic Euler-Lagrange equations to model muscle paths, providing insights into mechanobiology [1, 2].

Muscles are treated as massless, frictionless paths sliding smoothly over curved surfaces. Each muscle path, connecting its origin and insertion, is discretized into K linear segments, represented in $\gamma \in \mathbb{R}^{3(K+1)}$. Surface constraints ensure that the path adheres to the geometry without penetration or deformation. The geodesic Euler-Lagrange framework identifies the shortest viable muscle path while satisfying these constraints.

This method is applied to a shoulder model to study muscle paths, as shown in Fig.1A. The shoulder model consists of three bodies: the scapula, the humeral head, and the humeral shaft. It includes nine muscles, forming a complex musculoskeletal system (Fig.1B). The muscles are discretized into 25 elements. The shoulder is then simulated to undergo forward flexion from 0 to 150 degrees. Figure 1C shows the penetration between the humeral head and the nine muscles. The humeral head exhibits only minimal penetration (magnitude 10^{-9}), which is smaller than the tolerance and considered a numerical error. Therefore, it can be regarded as having no significant penetration during muscle movement. This demonstrates that our muscle model exhibits realistic movement and improved accuracy.



coordinate system   front view   penetration

Figure 1: (A) shoulder model with local coordinates for the scapula, humeral head, and humeral shaft. (B) front view of the shoulder model with 9 muscles. (C) penetration analysis between the humeral head and 9 muscles during shoulder flexion from 0 to 150 degrees. Yellow indicates no penetration. The penetration is smaller than the tolerance and can be considered a numerical error.

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[1] J. Penner and S. Leyendecker. A discrete mechanics approach for musculoskeletal simulations with muscle wrapping. Multibody System Dynamics 56(3), 267-287, 2022

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Analysis of forearm EMG to detect patterns of functional impairment in inflammatory arthritis patients

B. Coppers[1], S. Heinrich, V. Gracia-Ibanez [2], N. J. Jarque-Bou [2], S. Bayat[1], G. Schett[1],S. Leyendecker, A.M. Liphardt[1]

Rheumatoid arthritis (RA) and psoriatic arthritis (PsA) impact musculoskeletal function. These chronic conditions result in muscle weakness, proprioception deficits, and pain, primarily explained by concurrent inflammation. In lower limbs impaired muscle activity during isometric contraction might be caused by neurologically mediated inflammation [1]. Similarly, hand function relies on balanced flexor and extensor muscle strength. RA patients often struggle closing the fist, potentially due to inflammation in joints and reduced extensor strength [2]. Surface electromyography (EMG) is a valuable tool to explore the cause of these functional impairments by measuring muscle activity pattern. EMG can reveal deficits in muscle activation, coordination, and strength that are not always evident through other clinical assessments. Therefore, the hand function data set acquired in close cooperation of the Department of Rheumatology and Immunology, UKER and the Institute of Applied Dynamics, FAU including 73 RA, 76 PsA patients and 76 healthy controls (Ethics 357_20B) is used to analyse forearm muscle activity patterns during the performance of power Fig. (1, left) and precision grasps. This analysis focuses on exploring different EMG characteristics including amplitude and waveform parameters, as well as different normalization and post-processing steps of the EMG signal Fig. (1, right) to allow for group comparison and identify impairments, which are disease-related and help to better understand the neuromuscular consequences of arthritis.

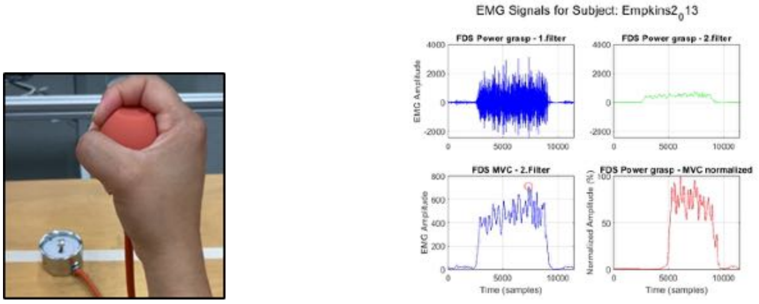

Figure 1: Flexor digtorium superficialis (FDS) muscle activity during the performance of a power grasp (left), highlighting different post-processing steps, like the normalization based on the maximum voluntary contraction(MVC) during an isometric grasping task.

Acknowledgments This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), SFB 1483, Project-ID 442419336, EmpkinS.

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[1] do Espirito Santo, R. C. et al. *Neuromuscular fatigue is weakly associated with perception of fatigue and function in patients with rheumatoid arthritis.* Rheumatol Int **38(3)**, 415-423 (2018).

[2] Brorsson et al . *Relationship between finger flexion and extension force in healthy women and women with rheumatoid arthritis* J Rehabil Med **44(7)**, 605-608 (2012).

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Robust muscle path modelling for arbitrary movements

Simon Heinrich, Xiyu Chen, Saulo Martelli[12], Peter Pivonka[12], Sigrid Leyendecker, Maxence Lavaill[12]

Determining muscle paths correctly and accurately is essential for musculoskeletal simulations, as the muscle path defines the muscle length, muscle length change, and the moment arm at origin and insertion [1]. Therefore, a robust muscle path determination that results in the correct muscle path for arbitrary motions is highly desired, e.g., the muscles in the arm behave the same during an elbow flexion-extension if the person is standing or walking. This means the muscle path should only depend on the relative motion of the involved bodies, not the added rigid body motion of the whole system.
We compute muscle paths using a geodesic muscle path model that was derived in the framework of discrete mechanics to yield a monolithic framework for the whole musculoskeletal dynamics [1]. This model describes the muscle path via nodes γ_k and ensures that the node does not penetrate the surface ($\phi(\gamma_k) \leq 0$), while yielding a path of minimal curvature. To improve the robustness with respect to arbitrary motions of varying complexity and velocity, we introduce a reparametrization of the muscle nodes relative to the bodies via ρ_γ, as in Fig. 1 on the left.
As can be seen in Fig. 1 on the right, this implementation yields consistent results for the static reference (computed at the finest time-grid with sparsity of 400) and every added rigid body motion (different plot colors) and the static reference, no matter the movement velocity. This improvement makes the used muscle path model viable for the investigation of even complex movement scenarios.

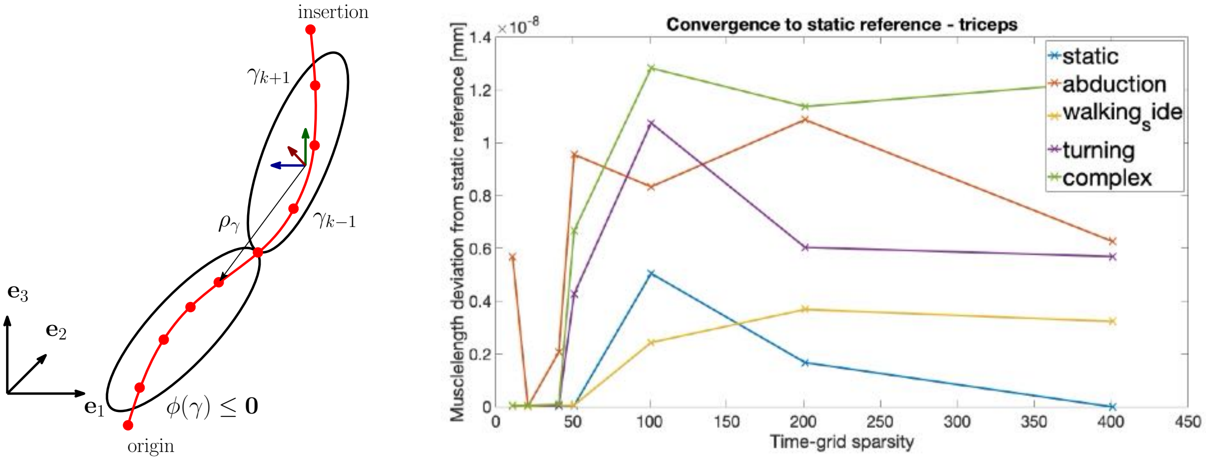

Figure 1: Left: sketch of the reparametrized muscle path. Right: difference in muscle length for the triceps with added arbitrary motions with respect to the static reference. A lower time grid sparsity value equals a faster movement.

Acknowledgements This work was partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Grant SFB 1483–Project-ID 442419336.

References

[1] J. Penner and S. Leyendecker. A discrete mechanics approach for musculoskeletal simulations with muscle wrapping. Multibody System Dynamics 56(3), 267-287, 2022

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[1] Mechanical, Medical and Process Engineering, Queensland University of Technology, Brisbane, Queensland, Australia
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A modified asynchronous variational integrator for phase field modeling of dynamic fracture

Deepak Jadhav, Dhananjay Phansalkar, Kerstin Weinberg[1], Michael Ortiz [2], Sigrid Leyendecker

Phase-field modeling of fracture has gained attention as a relatively simple yet fundamental technique for predicting crack propagation. In this work, we present our newly developed asynchronous variational integrator (AVI) for phase-field modeling of dynamic fractures. The AVI allows each mesh element to progress with its own time step [1]. In this new version named Globally Solved Asynchronous Variational Integrator (GSAVI), displacement updates occur as usual at each temporal update. However, instead of updating the phase field after every temporal update using an elemental patch [2], we solve for the phase field globally after the largest spatial element is updated. Figure 1 illustrates a boundary tension test (BTT) specimen along with its boundary conditions, used to investigate the characteristics of the new method. The distribution of the phase-field variable after the BTT specimen is fully broken is depicted in Figure 2. Significant computational savings achieved by the new method compared to its synchronous counterpart and the technique proposed by Niu *et al.* (2023) [2] are demonstrated in Figure 3. The convergence of the discrete action sum with spatial refinement, as depicted in Figure 4, signifies the reliability and robustness of the newly devised method.

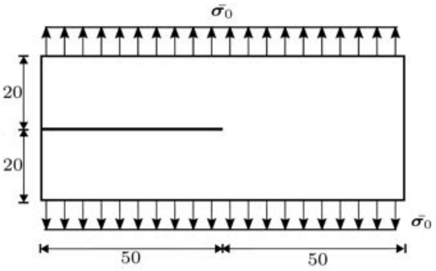

Figure 1: BTT specimen

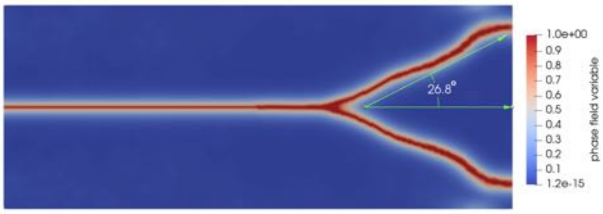

Figure 2: Phase field distribution of fully broken BTT specimen

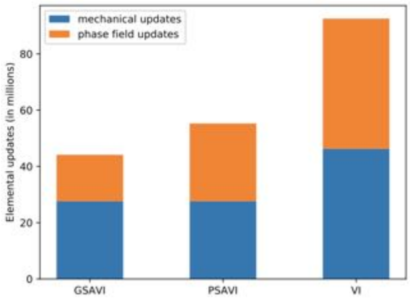

Figure 3: Comparison of elemental updates

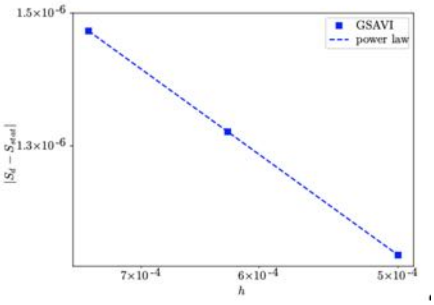

Figure 4: Convergence of discrete action sum

Acknowledgement: This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 377472739/GRK 2423/2-2023. The authors are very grateful for this support.

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[2] Z. Niu, V. Ziaei-Rad, Z. Wu, Y. Shen, *An asynchronous variational integrator for the phasefield approach to dynamic fracture*, International journal for numerical methods in engineering, 124, 434–457, 2023.

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Analysis of discrete Lagrangians defined for a new Lagrangian approach to optimal control of mechanical systems

Michael Konopik, Rodrigo T. Sato Martín de Almagro, Sigrid Leyendecker, Sofya Maslovskaya[1], Sina Ober-Blöbaum[1]

The optimal control of mechanical problems is widely used in today's technology centric world, but it is also important for scientific endeavors. Classical applications range from the optimal control of (industrial or medical) robots over trajectory planning for space missions and aircrafts to motion planning in sports or rehabilitation. Optimal control problems are typically not analytically solvable, thus it becomes necessary to employ numerical tools. The aim of this project is to analyze a new way of deriving optimality conditions [1], which reformulate the optimal control problem via a new control Lagrangian. This allows us to exploit the well-known machinery of Lagrangian systems to the optimal control context. We are analyzing the properties and structure of this new Lagrangian approach both in the continuous and discrete settings. We are also using the latter to derive symplectic integrators by approximating the corresponding discrete new Lagrangians [2].

In order to further investigate this new approach, in particular in the discrete setting, the following steps were undertaken:

In [1] it was then shown that the optimal control problem is equivalent to the augmented objective functions

$$\begin{aligned}\tilde{\mathcal{J}}^u(y,\dot{y},u) &= \Phi(q(T),\dot{q}(T)) + \lambda(T)\dot{q}(T) - \lambda(0)\dot{q}(0) + \mu(q(0)-q^0) + \nu(\dot{q}(0)-\dot{q}^0)\\ &\quad + \int_0^T \underbrace{\left[\frac{1}{2}g(q)(u,u) - \dot{\lambda}^T\dot{q} - \lambda^T\left(f(q,\dot{q}) + \rho(q)u\right)\right]}_{-\tilde{\mathcal{L}}^u(y,\dot{y},u)} \mathrm{d}t, \qquad (1\mathrm{a})\\ \tilde{\mathcal{J}}(y,\dot{y}) &= \Phi(q(T),\dot{q}(T)) + \lambda(T)\dot{q}(T) - \lambda(0)\dot{q}(0) + \mu(q(0)-q^0) + \nu(\dot{q}(0)-\dot{q}^0)\\ &\quad + \int_0^T \underbrace{\left[-\dot{\lambda}^T\dot{q} - \lambda^T f(q,\dot{q}) - \frac{1}{2}b(q)(\lambda,\lambda)\right]}_{-\tilde{\mathcal{L}}(y,\dot{y})} \mathrm{d}t, \qquad (1\mathrm{b})\end{aligned}$$

for $y = (q,\lambda)$ where q are the state variables and λ the costate variables, u the external control, $\rho(q)$ the injective linear anchor of the vector bundle that define the controls u, and f the vector field of the underlying mechanical system. Eqs. (1) further define the augmented optimal control Lagrangians $\tilde{\mathcal{L}}^u(y,\dot{y},u), \tilde{\mathcal{L}}(y,\dot{y})$.
To derive variational integrators from (1), it is necessary to define discrete objective functions first. This creates two difficulties: it is necessary to correctly discretize the new Lagrangians as well as the boundary terms.
This was accomplished by first defining an exact discrete new Lagrangian, establishing the equivalence with the continuous setting, (1), on a time-grid $\{t_k | k = 0,\dots,N\}$ of fix step-size $t_{k+1} - t_k = h$. This results in discrete new Lagrangians

$$\tilde{\mathcal{L}}_d^{u,e}(y_k, y_{k+1}, u_k, h) = \int_{t_k}^{t_k+h} \tilde{\mathcal{L}}^u(y,\dot{y},u)\mathrm{d}t, \qquad \tilde{\mathcal{L}}_d^{e}(y_k, y_{k+1}, h) = \int_{t_k}^{t_k+h} \tilde{\mathcal{L}}(y,\dot{y})\mathrm{d}t, \qquad (2)$$

for paths $y_k = (q_k,\lambda_k) = y(t_k), u_k = \{u(t) | t \in [t_k, t_{k+1}]\}$. The Lagrangians (2) further define discrete Legendre transforms [2] that allow us to canonically rephrase the continuous boundary conditions in (1) in the discrete setting:

$$\begin{aligned}\dot{q}(0) &= -D_1^{\lambda}\tilde{\mathcal{L}}_d^{u,e}(y_0, y_1, u_0^*) & \dot{q}(T) &= D_2^{\lambda}\tilde{\mathcal{L}}_d^{u,e}(y_{N-1}, y_N, u_{N-1}^*), & (3\mathrm{a})\\ \dot{q}(0) &= -D_1^{\lambda}\tilde{\mathcal{L}}_d^{e}(y_0, y_1) & \dot{q}(T) &= D_2^{\lambda}\tilde{\mathcal{L}}_d^{e}(y_{N-1}, y_n), & (3\mathrm{b})\end{aligned}$$

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[1] Universität Paderborn (UPB), Numerical Mathematics and Control (NMC)

for $\tilde{\mathcal{L}}_d^{u,e}$ and for $\tilde{\mathcal{L}}_d^{e}$ respectively and optimal controls u^*. Eqs. (2)-(3) let us define the discrete augmented objectives

$$\tilde{\mathcal{J}}_d^{u,e} = \Phi_d(q(T),\dot{q}(T)) + \mu(q_0 - q^0) + \nu(\dot{q}_0 - \dot{q}^0) + \lambda_T\dot{q}_T - \lambda_0\dot{q}_0 - \sum_{k=0}^{N-1}\tilde{\mathcal{L}}_d^{u,e}(y_k, y_{k+1}, u_k, h) \tag{4a}$$

$$\tilde{\mathcal{J}}_d^{e} = \Phi_d(q(T),\dot{q}(T)) + \mu(q_0 - q^0) + \nu(\dot{q}_0 - \dot{q}^0) + \lambda_T\dot{q}_T - \lambda_0\dot{q}_0 - \sum_{k=0}^{N-1}\tilde{\mathcal{L}}_d^{e}(y_k, y_{k+1}, h), \tag{4b}$$

As a next step, the optimality conditions of (4) were derived and their equivalence with the continuous setting shown. The results of the exact discrete setting were then used to consider a low-order integration scheme for which a properly discretized control-space was defined, their optimality conditions derived and finally applied to an example in the form of a low-thrust orbital transfer, for which a solution example is shown in fig. 1.

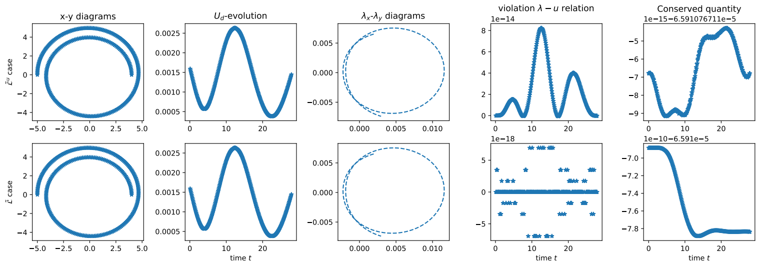

Figure 1: Low-thrust orbital transfer optimal control solution of e.g. a satellite revolving about Earth, starting at a radius $r = 4$ and ending at $r = 5$ within one and a half revolutions and a symplectic Euler scheme. From left to right: Cartesian state trajectory, evolution of U_d, Cartesian costate trajectory, preservation of $\lambda - u$ relation, and preservation of a conserved quantity of the optimal control system. Top/bottom are the $\tilde{\mathcal{L}}^u, \tilde{\mathcal{L}}$ systems.

Future work will focus on further analysis of the new Lagrangian approach properties and in particular its relation with the Hamiltonian approach defined by the regular Lagrangians in (1) as well as their conserved quantities, what meaning the symplecticity on the level of the control problem holds for the optimal control problem and how the numerical methods derived from the approximations of the discrete Lagrangian approach preserve these symmetries.

Acknowledgements

This project is funded by the Deutsche Forschungsgemeinschaft (DFG) with the projects: LE 1841/12-1, AOBJ: 692092 and OB 368/5-1, AOBJ: 692093.

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[2] J. E. Marsden, M. West. Discrete mechanics and variational integrators. *Acta numerica*, 10, 2001

Constitutive neural networks – automated model discovery for human cardiac tissue

D. Martonová, M. Peirlinck[1], K. Linka[2], G.A. Holzapfel[34], S. Leyendecker, E. Kuhl[5]

Constitutive models for the passive myocardium have been developed for many years. However, each model has its limitations when calibrating them simultaneously with different mechanical testing modes. Therefore, instead of selecting a specific constitutive model a priori and fitting its parameters to data, we utilize constitutive neural networks [1] to autonomously discover the best model and parameters to characterize the constitutive behavior of the passive human myocardium [2].

Assuming that the tissue is perfectly incompressible and orthotropic, we use data from triaxial shear and biaxial extension tests on human myocardial tissue [3] to train the neural network, see Figure 1(a). We learn the weights w by minimizing a loss function L

$$L(\mathbf{w};\mathbf{F}) = \frac{1}{n_{\text{data}}} \sum_{i=1}^{n_{\text{data}}} \|\,\sigma(F_i,\mathbf{w}) - \hat{\sigma}_i\,\|_2^2 + \alpha\,\|\,\mathbf{w}\,\|_1 \rightarrow \min \qquad \text{with} \qquad \|\,\mathbf{w}\,\|_1 = \sum_{i=1}^{n_{\text{weights}}} |\,w_i\,|, \tag{1}$$

where n is the number of data points, $\mathbf{F}$ is the deformation gradient, σ and σ_i are the modelled and measured Cauchy stresses, and $\alpha \geq 0$ is the penalty parameter of the lasso type regularisation to induce sparsity in the discovered model.

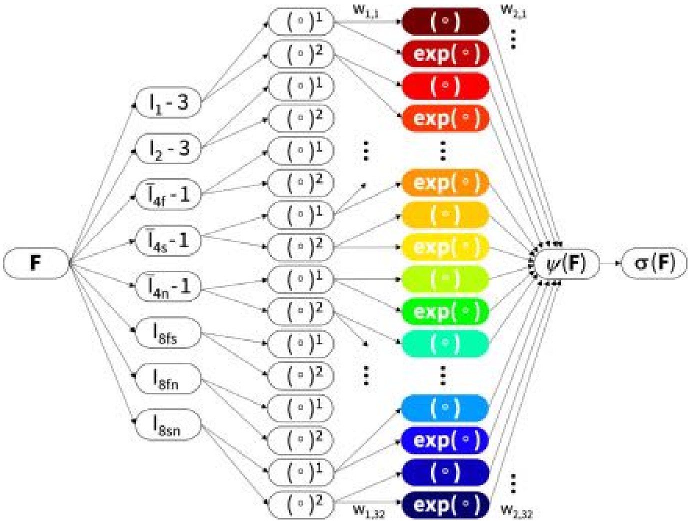

Figure 1: Orthotropic, perfectly incompressible, feed forward constitutive neural network with two hidden layers.

The neural network is successfully trained, firstly with the triaxial shear tests, secondly with the biaxial extension tests and thirdly with all tests simultaneously. Our results indicate that simultaneous training is essential for the accurate characterisation of the passive human myocardium. We systematically discover models with varying sparsity (see Figure 2) and goodness of fit and identify the best material model to represent the experimental data. It includes the isotropic invariant I_2 and the anisotropic invariants I_{4f} and I_{4n}.

We conclude that constitutive neural networks are capable of discovering the best model and their parameters to accurately reproduce different deformation modes of the human myocardium. Furthermore, the use of L_1-regularisation effectively reduces the model complexity without significantly decreasing the goodness of fit.

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[3] Institute of Biomechanics, Graz University of Technology, Graz, Austria
[4] Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[5] Department of Mechanical Engineering, Stanford University, Stanford, California, United States

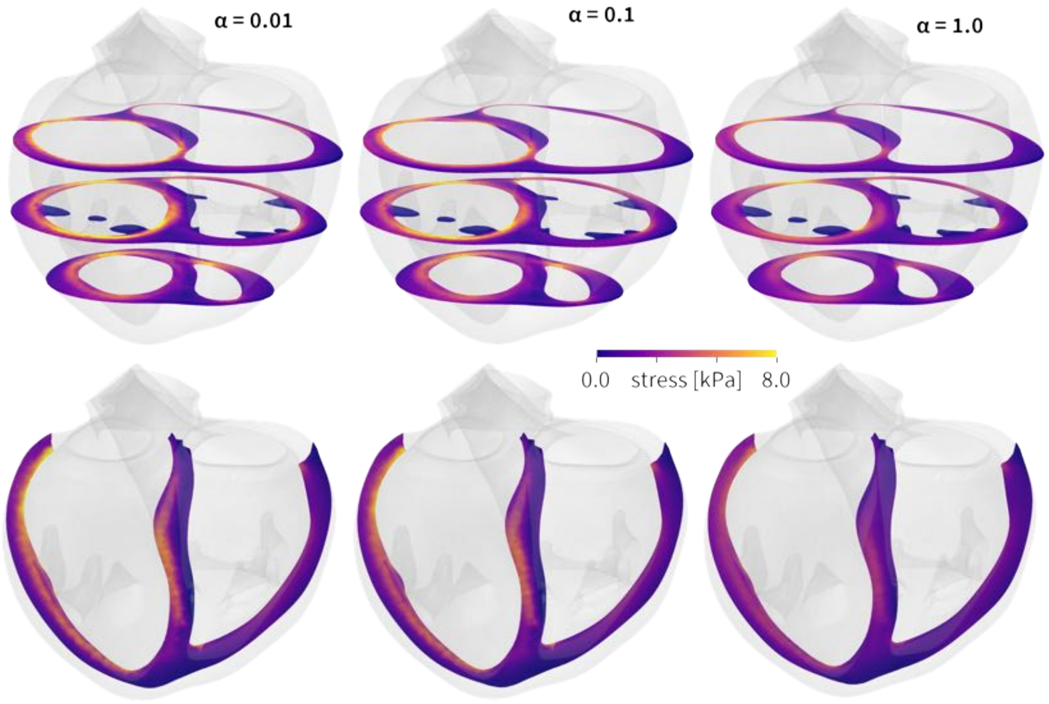

Figure 2: Stress profiles at the end of the diastole for different regularisation levels α.

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Structure preserving integrators for fracture simulations using peridynamics

Prateek, Giuseppe Capobianco, Sigrid Leyendecker

Peridynamics (PD) is a non-local continuum mechanics formulation, which overcomes the issues faced while modeling fracture using the classical formulation of continuum mechanics. In Peridynamics, force interactions between material points are not limited to the nearest neighbors, but are described as an integral over the neighborhood $\mathcal{H}_x$, as shown in Figure 1. Depending upon the method used to compute the force interactions, different formulations of PD exist, e.g., *bond-based*, *ordinary state-based*, *non-ordinary state-based* and *continuum kinematics-inspired*. For bond-based PD, the equations of motion of the point $\mathbf{x}$ are,

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathcal{H}_x} \mathbf{f}\left(\mathbf{u}(\mathbf{x}',t) - \mathbf{u}(\mathbf{x},t), \mathbf{x}' - \mathbf{x}\right) dV_{x'} + \mathbf{b}(\mathbf{x},t)\,, \tag{1}$$

where $\mathbf{f}$ describes the force interaction between $\mathbf{x}$ and $\mathbf{x}'$, $\mathbf{u}$ is the displacement function, and $\mathbf{b}$ are the body forces acting at $\mathbf{x}$. Since, the equations of motion and the material models are in integral form, they can be directly applied at the crack surface, unlike the classical models, which results in undefined spatial derivatives. Thus, PD theory is perfectly suitable for simulating fracture. The peridynamic (PD) formulation can also be applied to simple elastodynamic problems. As an example, the simulation of a planar bar using bond-based PD is presented in Figure 2. The simulation employs a horizon size of $\delta = 3.015h$, where h represents the grid spacing between the points. A constant load is applied on both ends of the bar. The displacement of the nodes on the left side is shown in Figure 2(c). The governing equations of motion are solved using the velocity Verlet scheme and oscillations are observed in the bar.

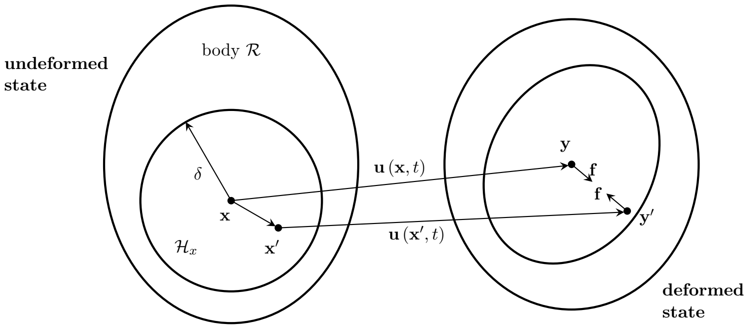

Figure 1: Definition of the horizon δ and neighborhood $\mathcal{H}_x$ of the point $\mathbf{x}$ in the body $\mathcal{R}$. Deformation of the material points $\mathbf{x}$ and $\mathbf{x}'$ develops an equal and opposite force in the bond-based PD model.

This project focuses on the development of structure-preserving integrators for fracture simulations using the PD formulation. The aim is to create numerical methods that conserve physical properties, such as energy or momentum, while accurately simulating the initiation and propagation of cracks in materials. By enhancing the stability and efficiency of peridynamic simulations, this work seeks to improve the modeling of material failure, enabling more reliable predictions in engineering applications involving fracture mechanics.

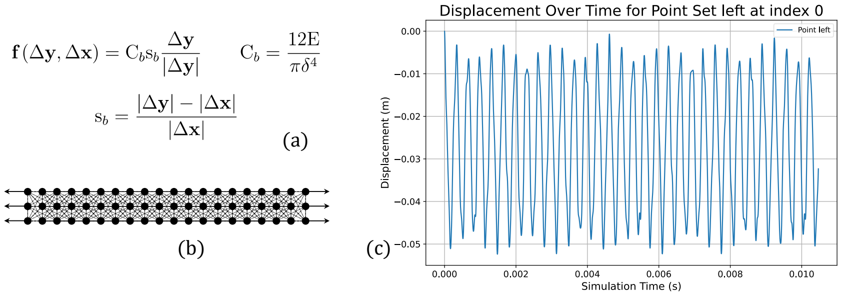

Figure 2: (a) Bond-based PD formulation to compute the pairwise force function using the bond constant C_b and bond stretch s_b. (b) Loading of 2D bar with constant force. (c) Displacement curve of the left face nodes of the 2D bar.

Variational integrators for constrained mechanical systems and optimal control

Rodrigo T. Sato Martín de Almagro, Sigrid Leyendecker

Geometric integration involves the numerical solution of differential equations using methods that intend to preserve some or all features or underlying structures that the original problem displays.

At our institute, a particular set of geometric integration methods we are interested in is variational methods [1, 2]. These are numerical methods tailored to systems whose behaviour can be derived from a variational principle, e.g. Hamilton's principle of stationary action, and related systems. These systems display important qualitative features that should ideally be present in the results of a simulation, such as conservation laws due to symmetries in the system (Noether's theorem) or compliance with specified constraints.

Variational methods have been widely applied in the numerical simulation of standard mechanical systems such as systems of particles and rigid bodies, as well as optimal control problems, where the dynamics are governed by ordinary differential equations. But these can also be applied to field theories, where the resulting equations are partial differential equations. These include the equations of finite strain elasticity, perfect fluids, electrodynamics, etc. The study and use of variational methods on fields is still not as extended or well-understood as in the former. For that matter, we are trying to understand the basics of these methods.

Currently we are focusing on the following topics:

- **Parallelized variational integrators.** Solving boundary value problems in the context of optimal control of particle systems can be a costly endeavour, particularly for real-time applications. We have analysed the convergence properties of parallelized versions of variational integrators for their implementation in graphics processing units (GPUs) [6]. This has also led us to study very interesting problems in the general theory of discrete Lagrangians. In particular, the discrete Jacobi equation, conjugate points, and the pathologies they bring.

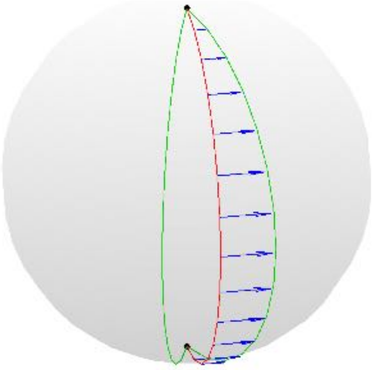

Figure 1: On the sphere and the kinetic Lagrangian, every pair of antipodal points is conjugate, i.e. there are infinitely many minimizing trajectories connecting them.

- **New control Lagrangian for controlled second order systems and Lagrangian systems.** In [7], we reframed particular cases of optimal control problems of second order systems into a Lagrangian framework. This allowed us to codify the problem into what we dubbed a new control Lagrangian, whose Euler-Lagrange equations provide the necessary conditions for optimality of the problem. We are currently generalizing the approach to more general optimal control problems of second order systems while deepening our understanding of the underlying geometry of the process. We have found that the geometry is intimately related to the *so-called* Tulczyjew's triple present in double tangent bundles.

- **Discretisation of new control Lagrangian.** We have also turned our attention to the discretisation of these new control Lagrangians. Surprisingly, it seems that the discretization of these new control Lagrangians, not only affords us symplectic integrators for the optimal control problem, but the resulting discretization of the state equations of the underlying system under control are, in certain cases, automatically symplectic too! To further formalise this study, we have developed a new definitions of semi-discrete new control Lagrangians, where the controls appear as continuous variables.

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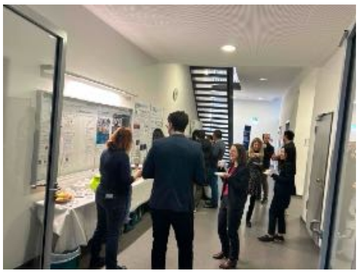
4 Activities

4.1 Network Meeting of the Alexander von Humboldt Foundation

This year, LTD was selected to host one event during the Network Meeting of the Alexander von Humboldt Foundation (Netzwerktagung der Alexander von Humboldt Stiftung). This event brought together doctoral and postdoctoral researchers from around the world, who are conducting their research in Germany through the support of the Alexander von Humboldt Foundation. The meeting provided an excellent opportunity for networking and featured interesting presentations.

The event began with four introductory presentations from the LTD group, showcasing our main research areas and a short demonstration of the innovative capabilities of our motion capture laboratory. After a productive break, researchers from different areas, shared insights into their work, highlighting the importance of the foundation's support in advancing their projects. The network meeting highlighted our institute's research, sparking interest among attendees and emphasizing the essential of networking in driving scientific progress.



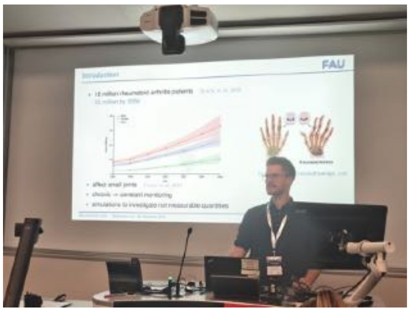
4.2 Phd award

In March 2024, the doctoral thesis of Dr.-Ing. Denisa Martonová was awarded with the Dr.-Klaus-Körper Preis by the International Association of Applied Mathematics and Mechanics (GAMM). In May 2024, the thesis entitled *"Computational modelling and simulation of rat heart electromechanics – from (smoothed) finite element methods towards a ligand-receptor model"* was elected to be presented during the finale of the ECCOMAS phd olympiad in Lissabon.

4.3 Collaboration with QUT

In 2024, Prof. Dr.-Ing. habil. Sigrid Leyendecker proudly continues her collaboration as an adjunct professor at the Faculty of Engineering, School of Mechanical, Medical and Process Engineering at Queensland University of Technology (QUT) in Brisbane, Australia. This enduring partnership consistently yields significant benefits, enriching both academic and cultural exchanges.

As part of the development of the SFB 1483 EmpkinS C04 project *Analysis of Degenerative Motion Impairments through Integration of Empathokinaesthetic Sensor Data in Biomechanical Human Models*, M.Sc. Simon Heinrich spent two months at QUT for an academic exchange, collaborating with Dr. Maxence Lavaill to further improve muscle path modeling for biomechanical simulations. Afterwards, he visited the *Combined Scientific Meetings* *of the Australian and New Zealand Society of Biomechanics (ANZSB) and the Australian and New Zealand Orthopaedic Research Society (ANZORS)*, where he presented on his work on marker data guided optimal control simulation of hand movement.



4.4 NMC – academic visit at LTD

During the first trimester of the year, we had the pleasure of hosting Prof. Dr.-Ing. Sina Ober-Blöbaum from the Research group Numerical Mathematics and Control (NMC) at the University of Paderborn. She was accompanied by postdoctoral researcher Dr. Sofya Maslovskaya. Their visit sparked insightful discussions on topics related to geometric numerical integration, optimal control, and in particular, Lagrangian methods. These exchanges led to deeper collaboration between the research group and our institute, and culminated in the joint work of several journal articles.

4.5 FRASCAL – academic visit at LTD

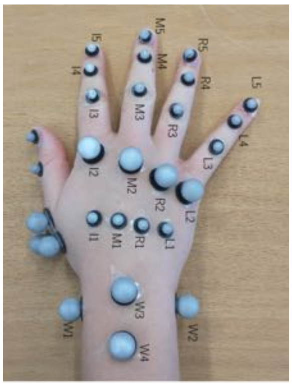
As part of the second cohort of the FRASCAL Project 09 on Adaptive Dynamic Fracture Simulation, we had the privilege of welcoming Prof. Dr. Michael Ortiz from the Division of Engineering and Applied Sciences, California Institute of Technology, alongside Prof. Dr. Kerstin Weinberg from the Chair of Solid Mechanics at the University of Siegen. Their visit to LTD earlier this year resulted in productive days focused on applied mechanics, in particular, fracture mechanics. This collaboration represents an opportunity to advance our research capabilities, exchange ideas, and further enrich our academic networks.

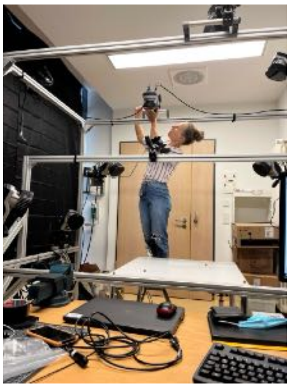
4.6 Motion capture laboratory

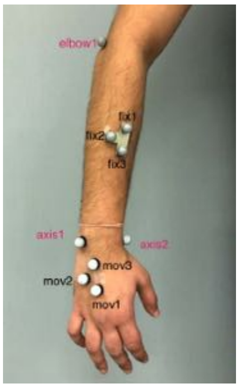
Our motion analysis lab is equipped with a state-of-the-art camera and marker-based optical tracking system. This includes 10 Qualisys MoCap high-speed cameras, 2 Qualisys high-speed video cameras, Noraxon MyoMotion inertial sensors, Cybergloves III for measuring hand joint angles, force plates, and Noraxon Desktop DTS electromyography sensors.

To facilitate motion capture for small-scale human movements, such as the motion of the hand, a frame was constructed to position the cameras closer to the markers. With this setup, the successful identification of kinematic parameters for joints in the human hand, including the wrist, metacarpophalangeal, and interphalangeal

joints, has been performed. This forms a crucial foundation for developing effective parameter identification procedures to create subject-specific models.
In 2024, the laboratory continues to be key for advancing motion capture studies, with a major focus on analyzing captured data. Impressively, 40% of our journal publications this year are linked to research conducted in various projects and collaborations at the motion capture laboratory at LTD over the past years.







4.7 CyberGlove

The analysis of hand movements can yield useful information and indicators for the detection of rheumatic diseases at an early stage. The CyberGlove project goal is to analyze whether the glove bears potential for this purpose. In a second step, we aim to measure activities of daily life and examine if the use of specific joints has an impact on the development of arthritis.

4.8 Editorial activities

Advisory and editorial board memberships Since 2014, Prof. Dr.-Ing. habil. Sigrid Leyendecker is a member of the advisory board of scientific journal Multibody System Dynamics, Springer. She is a member of the Editorial Board of ZAMM – Journal of Applied Mathematics and Mechanics / Zeitschrift für Angewandte Mathematik und Mechanik. She has been member of the council of the German Association for Computational Mechanics (GACM) as well as of the International Association for Computational Mechanics (IACM).

Since October 2022 she is the deputy department chairperson at the Department of Mechanical Engineering and since October 2023 the department chairperson of the Department of Mechanical Engineering at the Friedrich-Alexander-Universität Erlangen-Nürnberg.

5 Teaching

Winter semester 2024/2025

Dynamik starrer Körper (MB, ME, WING, IP, BPT, CE, MT)		
Vorlesung		S. Leyendecker
Übung + Tutorium		G. Capobianco, X. Chen D. Martonová, P. Prateek
Mehrkörperdynamik (MB, ME, WING, TM, BPT, MT)		
Vorlesung		G. Capobianco R.T. Sato Martín de Almagro
Praktikum Technische Dynamik – Modellierung, Simulation und Experiment (MB, ME, WING)		S. Leyendecker X. Chen, P. Prateek R.T. Sato Martín de Almagro
Praktikum Matlab (MB)		S. Leyendecker G. Capobianco

Summer semester 2024

Statik und Festigkeitslehre (BPT, CE, ME, MWT, MT)		
Vorlesung		S. Leyendecker
Übung + Tutorium		X. Chen, D. Holz D. Martonová, M. Stavole
geprüft	216 + 203 (WS 2023/2024)	
Biomechanik (MT)		
Vorlesung + Übung		G. Capobianco
geprüft	23 + 17 (WS 2023/2024)	
Geometric numerical integration (MB, ME, WING, BPT)		
Vorlesung + Übung		R.T. Sato Martín de Almagro
geprüft	21 + 2 (WS 2023/2024)	
Computational Multibody Dynamics (MB, ME, WING, BPT)		
Vorlesung + Übung		G. Capobianco
geprüft	3 + 0 (WS 2023/2024)	
Praktikum Matlab (MB)		
Teilnehmer	187	S. Leyendecker M. Stavole

Winter semester 2023/2024

Dynamik starrer Körper (MB, ME, WING, IP, BPT, CE, MT)

Vorlesung		S. Leyendecker
Tutorium + Übung		G. Capobianco, X. Chen D. Holz, E.S. Scheiterer
geprüft	225 + 85 (SS 2024)	

Mehrkörperdynamik (MB, ME, WING, TM, BPT, MT)

Vorlesung		G. Capobianco
Übung		R.T. Sato Martín de Almagro
geprüft	26 + 9 (SS 2024)	

Praktikum Technische Dynamik – Modellierung, Simulation und Experiment (MB, ME, WING)

Teilnehmer	11	S. Leyendecker E.S. Scheiterer, X. Chen D. Holz, R.T. Sato Martín de Almagro

Praktikum Matlab (MB)

Teilnehmer	172	S. Leyendecker M. Stavole

5.1 Theses

Doctoral theses

- Dr.-Ing. Martina Stavole
  Experimental characterisation, modelling and simulation of composite highly flexible beams – Application to unloaded shafts of flexible endoscopes
- Dr.-Ing. Eduard Sebastian Scheiterer
  Dynamic analysis of a human leg model with a prosthetic foot in the presence of polymorphic uncertainty

Master theses

- Patrick Buchner
  Discrete-time Exergetic Port-Hamiltonian Systems

Project theses

- Jan Hendrik Schlund
  Recursive computation of a nullspace matrix for constrained multibody systems

Bachelor theses

- Michael Wilsch
  Locomotion of a one-legged planar hopper through trajectory optimization

5.2 Seminar for mechanics

together with the Institute of Applied Mechanics LTM

17.12.2024 Dr. Julia Greenfield
Institute of Digital Medicine
Philipps-Universität Marburg & Universitätsklinikum Gießen und Marburg GmbH (UKGM)
Comparison of IMU and OMS data for analyzing spine movements

14.11.2024 Dr. Zohreh Ravanpakan
West University of Timisoara, Romania
Poisson bi-Hamiltonian systems on Lie groups: Algebra, Geometry and Dynamics

07.11.2024 M.Sc. Tengman Wang
Technische Universität München
Feedforward Control Design for Mechanical Structures

06.11.2024 M.Sc. Daniel Hübner
Friedrich-Alexander-Universtität Erlangen-Nürnberg
Chair of Applied Mathematics (Continuous Optimization)
Two-Scale Buckling Optimization of 3D Graded Lattice Structures using Numerical Homogenization based on Beam Models

29.08.2024 M.Sc. Alireza Sharifzadeh-Kermani
Animus Lab, Auckland Bioengineering Institute, NZ
A mechanistic approach for the brain pressure estimation

23.04.2024 Dr. Sofya Maslovskaya
Universität Paderborn

New Lagrangian approach in optimal control

18.04.2024 Dr.-Ing. Hagen Holthusen
Institute of Applied Mechanics
RWTH Aachen University
Material discovery with inelastic Constitutive Artificial Neural Networks (iCANNs)

5.3 Computational Multibody Dynamics

The course "Computational Multibody Dynamics" has been devised and taught by Dr.-Ing. Giuseppe Capobianco. During this course, the students learn to understand and implement a modular software for the simulation of multibody systems. After a concise treatment of the theory of multibody dynamics, the translation of the theory into a simulation software is discussed. This is complemented with several programming exercises enabling the students to gain practical experience and understanding of the modular software structure. By taking this course, the students will be able to

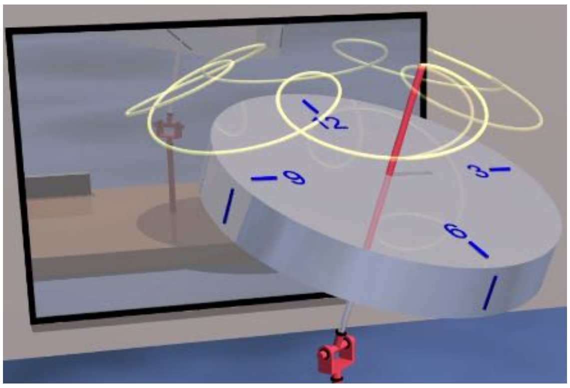
- write their own code for the simulation of complex multibody systems.
- understand what goes on "under the hood" of commercial multibody simulation software.

The course commenced in the winter semester of 2022/2023, and it is currently being offered every subsequent summer semester, consistently attracting a growing number of enrolled students.

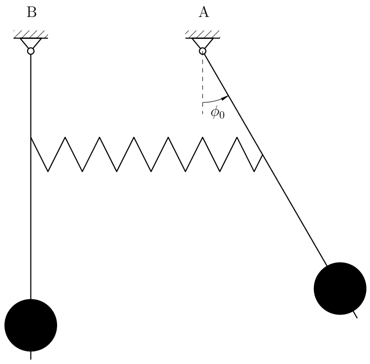
5.4 Dynamic laboratory

The laboratory couse Applied Dynamics – modeling, simulation and experiment (Praktikum Technische Dynamik) adresses all students of the Technical Faculty of the Friedrich-Alexander-Universität Erlangen-Nürnberg and it has recently been extended to include master's students specializing in Electromobility. Starting from the winter semester of 2023/2024, the laboratory course is conducted in English. The aim of the practical course is to develop mathematical models of fundamental dynamical systems to simulate them numerically and compare the results to measurements from the real mechanical system. Here, the students learn both the enormous possibilities of computer based modeling and its limitations. The course contains one central programming exercise and six experiments observing various physical phenomena along with corresponding numerical simulations:

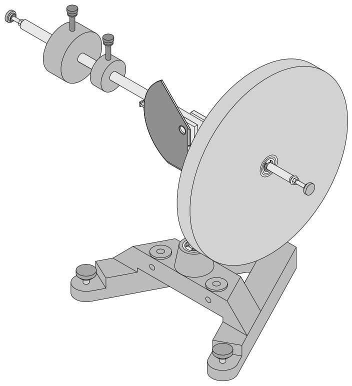
- programming exercise
- beating pendulums
- gyroscope
- ball balancer system
- robot arm
- inverse pendulum
- balancing robot



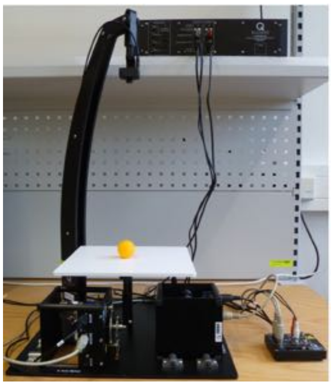
programming exercise



beating pendulums

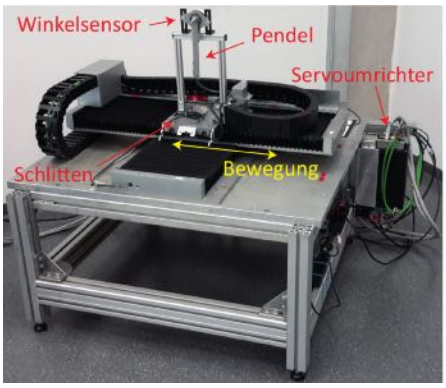


gyroscope



ball balancer system

robot arm



inverse pendulum

balancing robot

5.5 MATLAB laboratory

The Laboratory course MATLAB (Praktikum MATLAB) is available to all students at the Technical Faculty of Friedrich-Alexander-Universität Erlangen-Nürnberg, and it has recently been extended to include master's students specializing in Electromobility. Starting from the winter semester of 2023/2024, the laboratory course is conducted in English, which has led to a significant increase in student enrollment. To meet this heightened demand, the course's capacity has been doubled, and we aim to sustain this high level of interest in the upcoming semesters.

The primary objective of the course is to equip participants with essential skills in numerical programming using MATLAB. This collaborative effort involves the Institute of Applied Mechanics (LTM), the Institute of Production Metrology (FMT), and the Institute of Engineering Design (KTmfk).

The course commences with an introductory programming session covering MATLAB fundamentals. Subsequently, each institute introduces a task related to mechanics and engineering. For example, the LTD task involves understanding and simulating the dynamics of a crane. These tasks are presented to students through theory lectures, followed by hands-on programming sessions.

6 Publications

6.1 Reviewed journal publications

1. J. Bräunig, S. Heinrich, B. Coppers, C. Kammel, V. Wirth, M. Stamminger, S. Leyendecker, A.M. Liphardt, I. Ullmann and M. Vossiek. "A Radar-Based Concept for Simultaneous High-Resolution Imaging and Pixel-Wise Velocity Analysis for Tracking Human Motion", *IEEE Journal of Microwaves*, Vol. 4(4), pp. 639-652, DOI 10.1109/JMW.2024.3453570, 2024.
2. X. Chen and S. Leyendecker "Kinematic analysis of kinases and their oncogenic mutations – Kinases and their mutation kinematic analysis", *Molecular Informatics*, Vol. 43(5), DOI 10.1002/minf.202300250, 2024.
3. D. Martonová, M. Peirlinck, K. Linka, G. Holzapfel, S. Leyendecker and E. Kuhl. "Automated model discovery for human cardiac tissue: Discovering the best model and parameters", *Computer Methods in Applied Mechanics and Engineering*, Vol. 428, 117078, DOI 10.1016/j.cma.2024.117078, 2024.
4. E. S. Scheiterer, S. Heinrich, A. M. Liphardt and S. Leyendecker. "Marker position uncertainty in joint angle analysis for normal human gait – A new error-modelling approach" *Biomedical Signal Processing and Control*, Vol. 95, Part B, 106474, DOI 10.1016/j.bspc.2024.106474, 2024.
5. M. Nitschke, E. Dorschky,, S. Leyendecker, B. Eskofier, A. Koelewijn. "Estimating 3D kinematics and kinetics from virtual inertial sensor data through musculoskeletal movement simulations", *Frontiers*, Vol. 12, DOI 10.3389/fbioe.2024.1285845, 2024.
6. S. Heinrich, J. Michaelis, I. Reiher, B. Coppers, M. Lohmayer, E. Fleischmann, A. Kleyer, G. Schett, A.S. de Craemer, D. Elewaut, S. Leyendecker, A.M. Liphardt. "Comparison of CyberGlove III calibration methods and the application to arthritis patients", *IEEE Sensors*, Vol. 24(9), pp. 15283-15291, DOI 10.1109/JSEN.2024.3376606, 2024.
7. S. Fleischmann, S. Dietz, J. Shanbhag, A. Wünsch, M. Nitschke, J. Miehling, S. Wartzack, S. Leyendecker, B. Eskofier and A. Koelewijn. "Exploring Dataset Bias and Scaling Techniques in Multi-Source Gait Biomechanics: An Explainable Machine Learning Approach", *ACM Transactions on Intelligent Systems and Technolog*, DOI 10.1145/3702646, 2024.
8. I. Wechsler, A. Wolf, J. Shanbhag, S. Leyendecker, B. Eskofier, A. Koelewijn, S. Wartzack and J. Miehling. "Bridging the sim2real gap. Investigating deviations between experimental motion measurements and musculoskeletal simulation results – a systematic review". *Frontiers in Bioengineering and Biotechnology*, Vol. 12, 1386874, DOI 10.3389/fbioe.2024.1386874, 2024
9. G. Capobianco, J. Harsch, and S. Leyendecker. "Lobatto-type variational integrators for mechanical systems with frictional contact". *Computer Methods in Applied Mechanics and Engineering*, Vol. 418, 116496, 10.1016/j.cma.2023.116496, 2024.
10. V. Blazek, N. Loy, E. Jukic, B. Coppers, E. Fleischmann, J. Hübner, M. Iqbal, S. Heinrich, E.S. Scheiterer, S. Leyendecker, J. Greenfield, H. Labinski, M.G. Raimondo, A. Ramming, V. Schönau, G. Schett, J. Knitza and A.M. Liphardt. "Towards Objective Measurement of Spinal Mobility in Axial Spondyloarthritis – Benchmarking an Inertial Measurement Unit System With an Optical Measurement System", *Annals of the Rheumatic Diseases*, Vol. 83, pp. 1774-1775, DOI 10.1136/annrheumdis-2024-eular.5778, 2024.
11. N. Loy, V. Blazek, E. Jukic, E. Fleischmann, B. Coppers, J. Hübner, M. Iqbal, S. Heinrich, E.S. Scheiterer, S. Leyendecker, J. Greenfield, H. Labinski, M.G. Raimondo, A. Ramming, V. Schönau, G. Schett, J. Knitza and A.M. Liphardt. "Fear of Movement Affects Range of Motion During Repeated Basmi Exercises Assessed by State-of-the-Art Motion Capture Techniques", *Annals of the Rheumatic Diseases*, Vol. 83, pp. 936-937, DOI 10.1136/annrheumdis-2024-eular.5298
12. B. Coppers, S. Heinrich, S. Bayat, K. Tascilar, A. Kleyer, D. Simon, I. Minopoulou, G. Corte, F. Fagni, V. Schönau, D. Bohr, S. Leyendecker, G. Schett, A.M. Liphardt. "Reduced Hand Function Indicates Higher Disease Activity in Patients With Rheumatoid and Psoriatic Arthritis", *Annals of the Rheumatic Diseases*, Vol. 83, pp. 13421-13422, DOI 10.1136/annrheumdis-2024-eular.1112, 2024.

13. J. Breuling, G. Capobianco, S.R. Eugster and R.I. Leine. "A nonsmooth RATTLE algorithm for mechanical systems with frictional unilateral constraints", *Nonlinear Analysis: Hybrid Systems*, Vol. 52, pp. 101469, DOI doi.org/10.1016/j.nahs.2024.101469, 2024.
14. S. Leyendecker, S. Maslovskaya, S. Ober-Blöbaum, R.T. Sato Martín de Almagro, and F. Szemenyei. "A New Lagrangian Approach to Control Affine Systems With a Quadratic Lagrange Term", *Journal of Computational Dynamics*, Vol. 11, pp. 336-353, DOI 10.3934/jcd.2024017
15. M. Lohmayer, G. Capobianco and S. Leyendecker. "Exergetic port-Hamiltonian systems for multibody dynamics", *Multibody System Dynamics*, DOI 10.1007/s11044-024-10038-w, 2024.

6.2 Conferences and proceedings

1. S. Heinrich, B. Coppers, A.M. Liphardt and S. Leyendecker. "Optimal Control Simulation of Full Hand Flexion MovementsExploiting Optical Marker Tracking". *Scientific Meetings of ANZSB & ANZORS*, Melbourne, Australia, 1 - 4 December 2024.
2. D. Jadhav. D. Phansalkar, K. Weinberg, M. Ortiz and S. Leyendecker "A spatially adaptive phase field model for static and dynamic fracture", *IUTAM Symposium Computational Fracture Mechanics in Multi-Field Problems*, Bad Honnef, Germany, 8 - 13 December 2024.
3. S. Leyendecker. "Research at the Institute of Applied Dynamics". *Netzwerktagung der Alexander von Humboldt Stiftung*, Erlangen, Germany, 21 November 2024.
4. X. Chen, M. Lavaill, S. Heinrich, P. Pivonka and S. Leyendecker. "Comparison of muscle path predictions using OpenSim and anovel geodesic model". *Netzwerktagung der Alexander von Humboldt Stiftung*, Erlangen, Germany, 21 November 2024.
5. D. Martonová, M. Peirlinck, K. Linka, G. Holzapfel, S. Leyendecker and E. Kuhl. "Automated model discovery for human cardiac ttissue". *Netzwerktagung der Alexander von Humboldt Stiftung*, Erlangen, Germany, 21 November 2024.
6. M. Konopik. "Geometric numerical integration". *Netzwerktagung der Alexander von Humboldt Stiftung*, Erlangen, Germany, 21 November 2024.
7. D. Jadhav, D. Phansalkar, K. Weinberg, M. Ortiz and S. Leyendecker. "Simulating Dynamic Phase Field Fracture using a New Asynchronous Variational Integrator". *10th FRASCAL seminar*, Erlangen, Germany, 25 October 2024.
8. S. Leyendecker, D. Martonová and M. Stavole. "Structure preserving neural network-based methods − Euler's elastica and cardiac model discovery". *NUMDIFF-17 Conference on the Numerical Solution of Differential and Differential-Algebraic Equations*, Halle, Germany, 9 - 13 September 2024.
9. D. Jadhav, K. Weinberg, M. Ortiz and S. Leyendecker. "Phase Field Modeling of Dynamic Fracture using a Modified Asynchronous Variational Integrator". *ECF24 European Conference on Fracture 2024*, Zagreb, Croatia, 26 - 30 August 2024.
10. D. Martonová, M. Peirlinck, K. Linka, G.A. Holzapfel, S. Leyendecker and E. Kuhl. "Constitutive neural networks for model discovery of myocardial tissue", *CMBBE 19th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering*, 30 July - 1 August 2024.
11. G. Capobianco, J. Breuling and S. Leyendecker. "Nonsmooth Lobatto-type variational integrators based on the discretization of the virtual action". *ENOC European Nonlinear Dynamics Conference*, Delft, Netherlands, 22 - 26 July, 2024.
12. M. Stavole, R.T. Sato Martín de Almagro, G. Capobianco, O. Brüls and S. Leyendecker. "An augmented Lagrangian formulation of the planar elastica in constrained environments", *7th IMSD International Conference on Multibody System Dynamics*, Madison, Wisconsin, USA, 9 - 13 June 2024.
13. M. Lohmayer, O. Lynch, G. Capobianco and S. Leyendecker. "Recent progress on the EPHS modeling language: Multibody systems and discrete-time semantics". *2nd Brig Workshop on Dissipativity in Systems and Control*, Brig, Switzerland, 21 - 24 May 2024.

14. X. Chen, M. Lavaill, S. Heinrich, P. Pivonka and S. Leyendecker. "Comparison of muscle path predictions using OpenSim and a novel geodesic model". *DGfB Deutsche Gesellschaft für Biomechanik*, Heidelberg, Germany, 26 April 2024.
15. G. Capobianco, J. Breuling and S. Leyendecker. "Event-capturing simulation of nonsmooth systems". *GAMM Annual Meeting*, poster, Magdeburg, Germany, 18 - 22 March, 2024.
16. G. Capobianco, J. Breuling and S. Leyendecker. "A RATTLE integrator for the simulation of unilaterally constrained mechanical systems". *GAMM Annual Meeting*, Magdeburg, Germany, 18 - 22 March, 2024.

6.3 open-source code

1. E. Celledoni, E. Çokaj, A. Leone, S. Leyendecker, D. Murari, B. Owren, R. T. Sato Martíin de Almagro, M. Stavole (2024). "LearningEulersElastica" [Repository for the paper "Neural Networks for the approximation of Euler's elastica"]. Rretrieved from `https://github.com/ergyscokaj/LearningEulersElastica/`
2. S. Heinrich, J. Michaelis, I. Reiher, B. Coppers, M. Lohmayer, E. Fleischmann, A. Kleyer, G. Schett, A.S. de Craemer, D. Elewaut, S. Leyendecker, A.M. Liphardt (2024). "PyConnectCG3" [code to communicate with and calibrate the CyberGlove III using Python]. Retrieved from `https://github.com/Institute-of-Applied-Dynamics/PyConnectCG3`

7 Social events

Erlangen beer festival "Bergkirchweih"

Student summer grill

Pottenstein caves

Onboarding lunch of team members




Nikolaus hiking


Christmas dinner

Doctoral defenses

Farewell of team members