## Call for participation

## קול קורא להשתתפות

We invite you all to take part in GSC’23——the annual meeting of graduate students in the fields of Control and Systems Theory. The program of GSC’23 is attached herewith. It comprises talks by 13 Ph.D. and 5 M.Sc. students from various Israeli universities, and a tutorial talk by Professor Opher Donchin from BGU. As you will see, we are expecting a not-to-missed, high-level and thought-provoking event!

Attendance is open to all. However, for planning purposes, we kindly ask that you register at `https://forms.gle/gxQ5ij5ZF1GMYWh48` by the end of **May 3**. Registration will also secure a place at the (free) workshop lunch. Of course, speakers are registered by default.

We thank the Ben-Gurion University of the Negev Faculty of Engineering, and the departments of Biomedical Engineering and Mechanical Engineering for their generous comprehensive support!

As guest parking at the BGU campus is limited, we strongly advise arriving on campus by train. In special cases, a campus car entrance permit can be arranged. Such individual requests should be sent to `shnahum@bgu.ac.il`. Barkan Hall is located in Building 70 on the map below or Building 70A on the interactive map.

Looking forward to seeing you at GSC’23,

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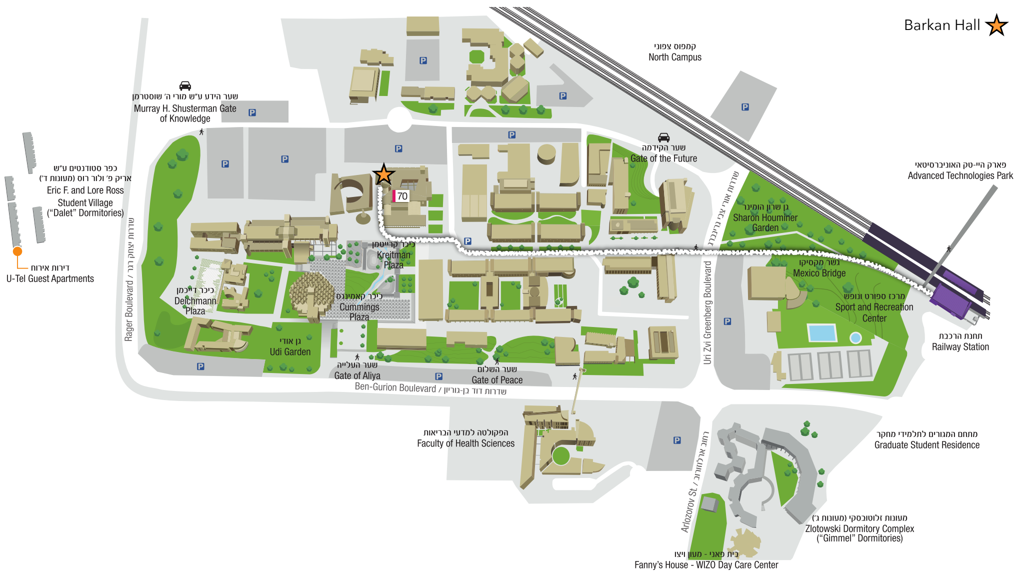
| ILANA NISKY & DAVID ZARROUK | GSC’23 Organizers |
| LEONID MIRKIN | IAAC President |




National Member Organization of IFAC and IAIN

Invitation to IAAC workshop

# Graduate Students in Systems and Control

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# GSC’23

to be held in **Barkan Hall**, Ben-Gurion University of the Negev
on Monday, May 8, 2023 (Iyar 17, 5783)

Organizers: **Ilana Nisky** & **David Zarrouk** (BGU)


We are grateful to the organizations below, whose support makes holding IAAC events possible

Applied Materials Israel Ltd.
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Shimon Peres Negev Nuclear Research Center

# Program

# תכנית

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|---|---|
| 08:45–09:15 | Gathering |
| 09:15–09:20 | Opening remarks |
| 09:20–09:50 | Tutorial Lecture: **Prof. Opher Donchin** (BME@BGU)<br>*Simplistic is not Wrong: Understanding the Motor System with 4 Parameters* |
| 09:50–10:10 | **Shani Arusi** (BME@BGU; supervisor: I. Nisky)<br>*A Model for Human Perception of Stiffness During Bimanual Interactions with Soft Objects* |
| 10:10–10:30 | **Shantanu Singh** (EE@TAU; supervisor: G. Weiss)<br>*A Class of Incrementally Scattering Passive Systems* |
| 10:30–10:50 | **Reut Nomberg** (BME@BGU; supervisor: I. Nisky)<br>*Human-in-the-Loop Analysis of Haptic Rendering with Time Delay—The Effect of Feedback Control with Delay in the Model of the Operator* |
| 10:50–11:05 | **Dan Navon** (CS@Technion; supervisor: H. Rotstein)<br>*A Robust Approach to Vision-Based Terrain Aided Localization* |
| 11:05–11:30 | Coffee / tea break |
| 11:30–11:50 | **Liraz Mudrik** (AE@Technion; supervisor: Y. Oshman)<br>*Terminal-Set-Based Optimal Stochastic Guidance* |
| 11:50–12:10 | **Yasan Safadi** (CEE@Technion; supervisors: J. Haddad & N. Geroliminis)<br>*Aircraft Departure Controller for Low Altitude Air City Transport: a Model Predictive Control approach* |
| 12:10–12:25 | **Itay Buchnik** (EE@BGU; supervisor: T. Routtenberg & N. Shlezinger)<br>*Latent-KalmanNet: Learned Kalman Filtering for Tracking from High-Dimensional Signals* |
| 12:25–12:45 | **Razi Zoabi** (CEE@Technion; supervisor: J. Haddad)<br>*A New Decentralized Time-Based Traffic Signal Control for Urban Road Networks* |

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|---|---|
| 12:45–12:50 | 2022 IAAC Award ceremony |
| 12:50–13:50 | Lunch break |
| 13:50–14:10 | **Nadav Cohen** (MT@Haifa U; supervisor: I. Klein)<br>*The BeamsNet Series: Data-Driven Methods for Improving Autonomous Underwater Vehicles' Navigation* |
| 14:10–14:30 | **Sergey Nazarov** (CEE@Technion; supervisors: Y. Agnon & P.-O. Gutman)<br>*A New Wind / Turbulence Estimation Method for Autonomous Rotorcraft* |
| 14:30–14:50 | **Ron Ofir** (EE@Technion; supervisors: M. Margaliot & Y. Levron)<br>*Contraction and $k$-Contraction in Lurie Systems with Applications to Networked Systems* |
| 14:50–15:05 | **Zitao Yu** (ME@Technion; supervisor: Y. Or)<br>*Nonholonomic Dynamics of Steer-Free Rotor-Actuated Twistcar* |
| 15:05–15:20 | **Zvi Chapnik** (ME@Technion; supervisor: Y. Or)<br>*Stability Transitions of Flexible Nano-Swimmer Under Rotating Magnetic Field* |
| 15:20–15:45 | Coffee / tea break |
| 15:45–16:05 | **Gal Barkai** (EM@Technion; supervisors: L. Mirkin & D. Żelazo)<br>*An Emulation Approach to Sampled-Data Synchronization* |
| 16:05–16:25 | **Omri Dalin** (EE@TAU; supervisor: M. Margaliot)<br>*The $k$-Comparison Principle* |
| 16:25–16:45 | **Shimon Regev** (ME@BGU; supervisors: S. Arogeti & A. Elyasaf)<br>*Designing Controllers for Non-cooperative Interactions with Multiple Objectives: A New Game-Theoretic Approach* |
| 16:45–16:50 | Closing remarks |

09:20–09:50

Tutorial Lecture. *Simplistic is not Wrong: Understanding the Motor System with 4 Parameters*
**Prof. Opher Donchin** (BME@BGU)

**Abstract:**
We will explore the motor system through two key ideas: noise and learning. We will see that the variability in our movements is multi-dimensional and that different dimensions of noise may serve different purposes. We will explore the possibilty that variability in our movements may help us learn.

09:50–10:10

*A Model for Human Perception of Stiffness During Bimanual Interactions with Soft Objects*
**Shani Arusi** (BME@BGU; supervisor: I. Nisky)

**Abstract:**
Estimating an object's stiffness, such as in the case of choosing ripe fruit, is usually done by squeezing it with our hands. We lack stiffness sensors in our hands; hence, the sensorimotor system relies on information about the amount of object deformation and the magnitude of the interaction forces to estimate stiffness. There are two assumptions about the way the interaction with the elastic object is controlled: 1) We can control the motion that causes a deformation of the object and measure the resulting force. Such stiffness is the ratio between the commanded deformation and the sensed force. 2) We can control the force that we apply on the object and measure its deformation. In this case, stiffness is defined as the inverse of compliance, the ratio between the commanded force and the sensed deformation. For an ideal elastic object, these two calculations yield the same value. However, the sensed information in the sensorimotor system needs to travel from the sensors in the hand to the stiffness estimator in the central nervous system, and the information arrives delayed compared with the sent motor command. This neural delay in the sensory feedback breaks the linear relation, which results in a higher estimation of the inverse of compliance estimation and a lower estimation of the stiffness estimated value compared with the nominal stiffness level. The sensorimotor system can calculate a weighted average between those estimations; equal weights to both estimates will result in the nominal stiffness level. However, uneven weights do not necessarily mean that the stiffness perception must be biased; even if the estimated stiffness is lower or higher than the nominal value, the absolute difference between the estimated values can remain correct. Perceptual biases will be revealed 1) when additional delay is introduced or 2) when there is asymmetry between the hemispheres such that the weights for each hand are different. Here, we developed a model that predicts based on difference between the hemispheres in stiffness judgment the effect of interaction with different objects touched by each hand separately. Participants probed pairs of virtual elastic objects and reported which object feels stiffer. They either touched both objects with the same hand or touched each object with different hands. In the first experiment, we found that right-handed participants perceived objects touched with the left hand harder than objects touched with the right hand. These biases can only be explained by asymmetric processing between the hemispheres. In addition, to better simulate our contact with real objects, we studied crossing boundary interactions which previously showed causing to the opposite biased direction than continuous interaction. Indeed, in our second experiment, we found the same asymmetry in the opposite direction, such that participants perceive objects touched with the left hand softer than objects touched with the right hand. These results are consistent with the model prediction and shed new light on the way the brain controls bimanual interactions with soft objects.

10:10–10:30

*A Class of Incrementally Scattering Passive Systems*
**Shantanu Singh** (EE@TAU; supervisor: G. Weiss)

**Abstract:**
The evolution of the state of distributed parameter systems (represented by linear partial differential equations) can be described by operator semigroups. Following the discovery of the Hille-Yoshida generation theorem in 1948, this theory became quite popular. The study of control and observation operators for such semigroups though relatively new, contains well established results for linear infinite dimensional systems with boundary inputs and boundary outputs. Extensive studies investigating systems described by linear partial differential equations with a nonlinear damping term, acting in the interior or on the boundary of the domain, have been conducted. As far as we are aware, most of the papers on this topic treat the well-posedness of the associated Cauchy problem. In our recent work we made an attempt to bridge this gap by considering nonlinear infinite-dimensional systems with both input and output signals, wherein the nonlinear (possibly set-valued) damping term was assumed to be defined on the entire state space. Using the theory of maximal monotone operators and Lax-Phillips semigroups, we have proved that such systems are incrementally scattering passive (hence well-posed). We also consider a special class of systems with a nonlinear (possibly set-valued) damping term that is only densely defined. This allows us to considerably enlarge the class of damping operators, to include also damping via boundary operators. We consider systems on the real Hilbert spaces. The state trajectories of the systems that we consider satisfy a certain differential inclusion. We show that this class of system has a unique generalized solution for any initial state in the state space and any locally square integrable input functions. Moreover, we show that such nonlinear systems are incrementally passive.

10:30–10:50

*Human-in-the-Loop Analysis of Haptic Rendering with Time Delay—The Effect of Feedback Control with Delay in the Model of the Operator*
**Reut Nomberg** (BME@BGU; supervisor: I. Nisky)

**Abstract:**
Most approaches to guaranteeing stability in haptic systems with delay do not consider the effect of the operator, thus resulting in conservative stability boundaries that limit the haptic feedback. Towards developing a human-centered stability analysis of haptic systems, we study here the effect of human feedback control on the stability of time-delayed haptic systems. We propose a coupled model to describe the haptic interaction of the operator with the haptic system, which includes the haptic device, the virtual environment, the haptic delay, the arm impedance, and a controller. The controller consists of feed-forward and feedback elements and contains a physiological delay. We present a methodology for the stability analysis of the model with the two time delays, one of which, the physiological delay, is constant and known. We demonstrate the stability boundaries and performance achieved by different feedback control architectures and show that the coupled system can enable stability and reasonable performance even with a high haptic delay. The results confirm that including the human operator in the stability analysis can significantly expand the boundaries of safe haptic feedback for use in haptic and teleoperation systems.

10:50–11:05

*A Robust Approach to Vision-Based Terrain Aided Localization*

**Dan Navon** (CS@Technion; supervisor: H. Rotstein)

**Abstract:**
Terrain-aided navigation (TAN) was developed before the GPS era to prevent the error growth resulting from inertial navigation. TAN algorithms were initially developed to exploit altitude over ground or clearance measurements from a radar altimeter in combination with a Digital Terrain Map (DTM) in either batch or epoch-by-epoch fashion. After almost two decades of silence, the availability of inexpensive cameras and computational power together with the need to find efficient GPS-denied positioning solutions, has prompted a renewed interest in this solution. Vision-based TAN is in many aspects more challenging than the original one; for one, visual observations can only provide range up to a scale, hence preventing a straightforward extension of classical TAN techniques. In order to solve the visual SLAM problem, one has to use additional apriori information regarding the scene. The purpose of this paper is to extend a two-view approach to TAN presented a few years ago to solve the multiple-view case using the Bundle Adjustment algorithm. The approach considered here splits the problem into two parts: in the first, given a series of images from a monocular camera, and a corresponding, valid DTM, which is freely available in many areas: visual, 2D features are extracted and matched across successive images and a classical BA problem is solved to obtain a scale-free model of the observed environment. In the second, the point cloud is adjusted to fit the DTM using an algorithm resembling point-to-plane Iterative Closest Point (ICP), which is well-studied in the computer vision community. Between the two stages, ray-tracing is used to assign visual features to the 3D world as modeled by the DTM. Using the presented algorithm the scale is deduced and applied over the BA's scale-free solution. When running experiments of the algorithm described above, it became clear that in order for the algorithm to work on actual data, care must be taken to detect and remove outliers resulting from an incorrect assignment of scale-free points to features in the DTM. Indeed, a robust algorithm must use all available cues to remove problematic points resulting from BA errors or incorrect terrain anchoring. The algorithm presented here exploits various considerations, including terrain's geometric to remove features with large a priori sensitivity, scales statistics to detect false associations, local analysis to reject relatively complex terrain patches, and multiple-stage optimization aimed at achieving relatively small residuals. The main contributions of the paper are the introduction of a new, more flexible, and efficient algorithm for solving the visual-assisted TAN. The algorithm combines two fast stages for solving the problem. Between the two stages, a new outlier-rejection step is introduced to make the algorithm robust and suitable for real-world data. To validate the algorithm, both a synthetic and a simulated environment were considered on which performance can be assessed. This is important since eventually the TAN localization algorithm will most probably be used in combination with inertial navigation hence requiring error level and correlation stamps.

11:30–11:50

*Terminal-Set-Based Optimal Stochastic Guidance*

**Liraz Mudrik** (AE@Technion; supervisor: Y. Oshman)

**Abstract:**
We address a stochastic interception scenario, where the intercepting missile has only uncertain information about the target's state, which it infers from noisy measurements. We realistically assume that the interceptor cannot know the true maneuvering dynamics of the target. Adopting a worst-case strategy, it can assume that the target possesses ideal dynamics, and compensate for the aforementioned dynamic model imperfections by adding process noise to the model. We assume that the target selects its control law from a given admissible control set, and that it randomly changes its mode according to a known Markov chain, thus rendering its dynamics hybrid. When designing an optimal guidance strategy in stochastic settings, even when linear models and Gaussian noises are assumed, the notorious curse of dimensionality renders prominent solutions to this problem, such as dynamic programming and model predictive control, intractable for real-time applications. We use an approach based on the notion of terminal sets to develop an optimal interception strategy for such scenarios. We show that this approach drastically alleviates the computational burden without loss of optimality. Following the guidelines of the generalized separation theorem, we provide the guidance law with the posterior probability density function (PDF) of the target's state. This PDF is computed using an independently-designed interacting multiple model (IMM) estimator, which is known to be a highly efficient estimator for hybrid systems. The IMM provides a Gaussian mixture model (GMM) representation of the posterior PDF with a time-invariant number of modes. We first show that, based on the outputs of the IMM, the target terminal set has a GMM distribution with an exponentially increasing (in time) number of modes. Then, we establish that these modes can be optimally merged, yielding just a quadratic increase in the number of modes. Another computational burden reduction is achieved via a novel decomposition of the interceptor's terminal set. These results render the proposed strategy implementable in real-time, as the horizon is sufficiently short at the endgame stage of the engagement. A Monte Carlo simulation study is used to demonstrate the performance of the novel guidance law in stochastic scenarios, and to show

that it achieves real-time performance despite its (still) considerable computational burden.

11:50–12:10

*Aircraft Departure Controller for Low Altitude Air City Transport: a Model Predictive Control approach*

**Yasan Safadi** (CEE@Technion; supervisors: J. Haddad & N. Geroliminis)

**Abstract:**

Low-altitude aircraft is being developed as a new mode of urban transport. This will give rise to new urban air transport systems, called low-altitude air city transport (LAAT) systems. Such systems will include aircraft operated with or without pilots, transferring passengers and goods in urban areas using low-altitude levels of urban airspace. Recent works [1,2,3] show that the Macroscopic Fundamental Diagram (MFD) is a powerful tool for understanding LAAT systems from a theoretical perspective and allows us to detect, model, and minimize congestion conditions in the airspace. This research established a new LAAT plant model that captures the microscopic and macroscopic levels in order to identify the airspace traffic conditions, see [2]. The work implemented an aircraft collision-avoidance model with cooperative distributed control algorithms from the literature, using the Artificial Potential Field (APF) approach, to describe the low-altitude aircraft interactions, i.e. implying the microscopic traffic behavior. Simultaneously, using the generalized definitions of Edie, the macroscopic traffic flow variables are determined for LAAT networks. Different case study examples were simulated to analyze the full shape of MFD curves for LAAT systems, considering different algorithms (waypoints and destination plane), aircraft, and airspace settings. Additionally, a unique modeling framework for LAAT operation and a real-time synchronized implementation of large-scale LAAT simulation were developed.

The development of the LAAT simulation environment, and the identification of airspace traffic conditions, lead to the development of aggregate models and new model-based control strategies to minimize congestion in futuristic urban airspace, where an aircraft departure controller for LAAT systems is developed and evaluated, see [3]. For this reason, a unique LAAT framework is developed that couples modeling and control LAAT systems, and integrates the two aggregation levels, i.e., microscopic and macroscopic, by combining the plant model from [2] with the development of a new control model at the macroscopic level, an accumulation-based model for distributed regions. Then, based on the developed framework, an optimal control strategy is formulated to optimize the aircraft inflow rate by manipulating their departure times to mitigate congestion. Different control strategies are tested: Greedy Controller and Model Predictive Controller. The strategies are deployed for the whole network or for each region at the macroscopic level and then transformed to the microscopic level. This research contributes to the literature with a novel LAAT framework that (i) models the air traffic flow and (ii) implements model-based traffic control strategies which aim to reduce congestion in LAAT systems.

12:10–12:25

*Latent-KalmanNet: Learned Kalman Filtering for Tracking from High-Dimensional Signals*

**Itay Buchnik** (EE@BGU; supervisor: T. Routtenberg & N. Shlezinger)

**Abstract:**

The Kalman filter (KF) is a widely-used algorithm for tracking dynamic systems that are captured by state space (SS) models. The need to fully describe a SS model limits its applicability under complex settings, e.g., when tracking based on visual data, and the processing of high-dimensional signals often induces notable latency. These challenges can be treated by mapping the measurements into latent features obeying some postulated closed-form SS model, and applying the KF in the latent space. However, the validity of this approximated SS model may constitute a limiting factor. In this work, we study tracking from high-dimensional measurements under complex settings using a hybrid model-based/data-driven approach. By gradually tackling the challenges in handling the observations model and the task, we develop Latent-KalmanNet, which implements tracking from high-dimensional measurements by leveraging data to jointly learn the KF along with the latent space mapping. Latent-KalmanNet combines a learned encoder with data-driven tracking in the latent space using the recently proposed-KalmanNet, while identifying the ability of each of these trainable modules to assist its counterpart via providing a suitable prior (by KalmanNet) and by learning a latent representation that facilitates data-aided tracking (by the encoder). Our empirical results demonstrate that the proposed Latent-KalmanNet achieves improved accuracy and run-time performance over both model-based and data-driven techniques by learning a surrogate latent representation that most facilitates tracking, while operating with limited complexity and latency.

12:25–12:45

*A New Decentralized Time-Based Traffic Signal Control for Urban Road Networks*

**Razi Zoabi** (CEE@Technion; supervisor: J. Haddad)

**Abstract:**

This paper proposes a new approach to traffic signal control that prioritizes minimizing accumulated travel time delays over maximizing throughput. The study proposes a new policy for max-pressure traffic signal control that considers the spatial distribution of queues and vehicle accumulated travel time delay using queuing theory literature. This approach offers a new time-oriented max-pressure with stability guaranty. The proposed models were evaluated through extensive simulations on complex traffic networks of varying sizes and demand levels and compared with existing max-pressure algorithms. The results demonstrate that the proposed models outperform existing algorithms in all metrics, especially in stabilizing the accumulated delay of vehicles, even under high-demand and complex network conditions. The proposed approach is robust and stable under varying demand conditions, making it suitable for practical deployment in real-world traffic networks. Previous max-pressure policies neglect secondary low demand movements thus could lead to red-light violations, ultimately compromising the safety of the transportation system. Overall, this study highlights the potential of using accumulated travel time as an effective performance metric in developing more efficient and sustainable traffic sig-

nal control systems. This approach could contribute significantly to traffic flow efficiency and have positive implications for urban mobility, reducing congestion, and improving air quality.

13:50–14:10

*The BeamsNet Series: Data-Driven Methods for Improving Autonomous Underwater Vehicles' Navigation*

**Nadav Cohen** (MT@Haifa U; supervisor: I. Klein)

**Abstract:**

Autonomous underwater vehicles (AUV) are used to perform scientific tasks at the great depths of the ocean. Commonly, an inertial navigation system (INS) aided by a Doppler velocity log (DVL) is used to provide the vehicle's navigation solution. In such fusion, the DVL estimates the AUV's velocity vector which, in turn, determines the accuracy of the navigation solution. The DVL measures four beam velocities and utilizes them to estimate the vehicle velocity vector. However, in real-world scenarios, the DVL may receive only partial beam measurements or be in a complete outage (no measurements). These scenarios may occur when passing over tranches on the seafloor, extreme pitch and roll maneuvers (such as diving), sea creatures blocking the sensor and more. When only one beam measurement is missing, the AUV velocity vector can still be estimated but with a substantial error. When two beam measurements, or more, are missing, the AUV velocity measurement cannot be estimated. Consequently, the navigation solution relies only on the inertial navigation solution, which drifts in time due to error accumulation in the inertial sensors. To improve the AUV's navigation accuracy and robustness, an end-to-end deep learning framework called BeamsNet was developed. Sea experiments in the Mediterranean Sea were conducted with a mid-size ECA GROUP AUV, the "Snapir" AUV, for training and testing our approach. The dataset was created by collecting DVL and inertial sensor data from nine different missions performed by the AUV with a total time duration of approximately four hours. The DVL works at a rate of 1Hz which translates to 13,886 DVL measurements and the inertial sensors operate at a rate of 100Hz, corresponding to 1,388,600 measurements. Each mission had different parameters regarding the length of the mission, objective, AUV speed, operational depth, and the maneuvers it performed. First, in the case of normal DVL conditions (four beam measurements), two versions of BeamsNet that utilized past DVL measurements, and one version that also used inertial data readings, were able to improve the AUV velocity vector by more than 50% in comparison to the known model-based approach. Secondly, in partial DVL measurements, a common case of two missing DVL beams was examined. In this scenario, the model-based approach cannot provide an estimate of the velocity vector. A modified BeamsNet architecture was derived, enabling a velocity vector estimate with up to 7.2% speed error. Lastly, a scenario of a complete DVL outage was observed and Set-Transformer-based BeamsNet was able to regress the AUV velocity vector with an 8.547% speed error. To conclude, all the scenarios listed above can be evaluated accurately with BeamsNet versions. Thus, it can be implemented to improve real-time AUV navigation and also be used to give better navigation results to lower-cost IMUs and DVL sensors and thereby reduce the cost of these extremely expensive AUVs.

14:10–14:30

*A New Wind / Turbulence Estimation Method for Autonomous Rotorcraft*

**Sergey Nazarov** (CEE@Technion; supervisors: Y. Agnon & P.-O. Gutman)

**Abstract:**

Atmospheric wind and turbulence significantly affect autonomous helicopters' navigation calculations, flight efficiency, control performance, and flight safety. Therefore, estimating the wind conditions and current turbulence level in flight is critical. The classic method for fixed-wing aircraft consists in using the wind triangle. The wind can be estimated if the true airspeed (TAS) is known from the air data system and the ground speed (GS) vector is known from the navigation system. However, this method assumes that TAS is known, while most small rotorcrafts are not equipped with angle-of-attack and side-slip sensors. It is often assumed that the measured Indicated Airspeed (IAS) is approximately equal to TAS. While this assumption may be valid for fixed-wing aircraft, it is unacceptable for a rotorcraft that can fly with high slip angles. This study describes a new original in-flight algorithm for wind/turbulence field estimation using a standard unmanned rotorcraft sensor kit and control signals produced by the flight control system. This approach does not assume steady flight, like other existing methods, but it remains to investigate the characteristics of flight and wind patterns for which the sought disturbance vector is observable. As a basic model of helicopter dynamics, a linear identified model is proposed, which is used for the flight control design and is available for all UAS projects. Linear models were identified and verified for several anchor points within the flight envelope. These discrete-point linear models and trim data were combined into a full flight-envelope simulation model based on a comprehensive model stitching architecture. For this preliminary study, one linear forward-flight helicopter model was selected and modified into a quasi-nonlinear model by adding trim data and nonlinear kinematic equations. A nonlinear Unscented Kalman filter was used with the quasi-nonlinear helicopter model and the scaled unscented transformation (UT) to estimate wind components in the North-East-Down (NED) frame. The resulting estimate is split using moving averaging into the steady horizontal wind and atmospheric turbulence. The algorithm was tested on a continuous model-stitched simulation in which the wind and atmospheric turbulence were simulated with the Dryden model. The result was successfully applied to the actual BE-50 helicopter flight test data.

14:30–14:50

*Contraction and $k$-Contraction in Lurie Systems with Applications to Networked Systems*

**Ron Ofir** (EE@Technion; supervisors: M. Margaliot & Y. Levron)

**Abstract:**

A Lurie system is the interconnection of a linear time-invariant system and a nonlinear feedback function. We derive a new sufficient condition for $k$-contraction of a Lurie system. For $k = 1$, our sufficient condition reduces to the standard stability condition based on the bounded real lemma and a small gain condition. However, Lurie systems often have more than a single equilibrium and are thus not contractive with respect to any norm. For $k = 2$, our condition guarantees a well-ordered asymptotic behaviour of the closed-loop system: every bounded so-

lution converges to an equilibrium, which is not necessarily unique. As such, in contrast to the standard condition, our approach allows the analysis of multistable systems. We demonstrate our results by deriving a sufficient condition for $k$-contraction of a general networked system, and then applying it to guarantee $k$-contraction in a Hopfield network, a nonlinear opinion dynamics model, and to study global stability in a 2-bus power system.

14:50–15:05

*Nonholonomic Dynamics of Steer-Free Rotor-Actuated Twistcar*

**Zitao Yu** (ME@Technion; supervisor: Y. Or)

**Abstract:**

The dynamics and control of underactuated wheeled vehicles governed by nonholonomic constraints have been an extensively researched topic for decades. Open-loop Control of such systems can be achieved by choosing different gaits of periodic inputs, which enables steering such system along desired paths. One of the classic examples is the Snakeboard [1], which is actuated by controlling the wheels' heading angles and an oscillating rotor attached to the body. Another example is the Twistcar [2], in which the joint connecting the body and steering link is periodically actuated, either by prescribing the steering angle or the mechanical torque. Asymptotic analysis of the Twistcar revealed abundant nonlinear phenomena in its dynamics, such as movement direction reversal depending on the vehicle's structure [2]. In both works, all internal shape variables are actuated. Moreover, due to lack of dissipation in the models, the body motion shows growing oscillations superposed on the unboundedly growing mean value.

In this work, we introduce the combined model Steer-free Rotor-actuated Twistcar. It has a single actuation of an oscillating inertial rotor angle $\psi(t)$ relative to the body, while the steering joint angle is passive, and evolves dynamically. In addition, we consider viscous dissipation caused by the wheels' rolling resistance, and possibly damping of the passive steering joint. Interestingly, this results in existence of periodic solutions of the system, in which the dissipated mechanical energy per cycle is balanced by the energy input of the actuation. Invariance properties of the vehicle's dynamics enable some reduction of the system's dimensionality, and numerical integration is utilized for seeking periodic solutions and analysing their orbital stability via the evaluation of Floquet multipliers. We find multiplicity of periodic solutions, some are stable (i.e., convergent from nearby perturbed initial states) while others are unstable (i.e., divergent). Continuously varying a single parameter of the system while tracking all branches of periodic solutions reveals interesting bifurcations and stability transitions. Symmetric periodic solution $\bar{\phi} = 0$, having zero net body rotation, changes from unstable to stable through a subcritical pitchfork bifurcation where a pair of unstable asymmetric branches evolve. Furthermore, these two unstable asymmetric branches introduce another critical transition, which is fold (saddle-node) bifurcation where the unstable asymmetric solution branches fold back into stable asymmetric branches. Remarkably, this implies that for some regions of the parameters, the only stable periodic solution is symmetric, while in another region the only stable solutions are pair of asymmetric ones, and in an intermediate region the systems exhibit multi-stability of symmetric and asymmetric solutions. Input to such a system is a single sinusoidal signal, which enables an easier analysis of the dynamics. Further control strategies may be investigated after deeper understanding of this dynamical system.

15:05–15:20

*Stability Transitions of Flexible Nano-Swimmer Under Rotating Magnetic Field*

**Zvi Chapnik** (ME@Technion; supervisor: Y. Or)

**Abstract:**

Inspired by the motion of bacteria and other microorganisms, researchers have developed artificial nano-structures that can be propelled upon a suitable stimulation by external energy sources. These devices attract much interest because of their great potential for bio-medical purposes. The most common strategy is actuating magnetically responsive structures that revolve around their long axis when they are actuated using rotating magnetic fields, resulting in corkscrew locomotion.

Our previous joint work presented fabrication and actuation of a simple magnetic nano-swimmer, two rods connected by a elastic hinge. Experiments under different actuation frequencies result in different motion phases. At low frequencies in-plane tumbling; at a higher frequencies, moving forward in a spatial helical path in synchrony with the rotating magnetic field; in further frequency increase, asynchronous swimming is obtained. Furthermore, we presented a simplified two-link model of the swimmer and conducted numerical simulations of its nonlinear spatial dynamics, obtaining qualitative agreement with experimental observations.

In this contribution, we revisit the two-link model and explicitly formulate and analyze its nonlinear 7 DOF dynamic equations. For the synchronous motion, we reduced the dynamic equations to 4 DOF time-invariant system using transformation of variables. For the first time, we obtained explicit semi-analytic solutions of this motion under simplifying assumptions, in both in-plane, helical swimming synchronous regimes. We conduct stability analysis of the solutions and obtain an explicit expression for the forward speed. We also obtain closed-form expressions of the critical transitions frequencies. Using perturbation expansion in the limit of low stiffness, we develop an approximate formulation of the helical motion, allowing to find the optimal frequency and swimming speed analytically. Finally, we present numerical analysis of the influence of additional effects, as well as parametric optimization of the swimmer's performance.

15:45–16:05

*An Emulation Approach to Sampled-Data Synchronization*

**Gal Barkai** (EM@Technion; supervisors: L. Mirkin & D. Żelazo)

**Abstract:**

This work presents a novel approach for achieving state synchronization of homogeneous LTI agents to a trajectory generated by a prescribed reference generator under intermittent and asynchronous communication. The proposed protocol involves emulating "ideal" global analog dynamics at each agent to generate the control signal between samples. Each agent transmits the centroid state of its local emulator rather than its own state vector. When an agent receives

new information it is then used to update the state vector of its local emulator. Using this paradigm it is possible to guarantee synchronization under mild assumptions on the system's structure, persistency of connectivity, and uniform boundedness of sampling intervals. Additionally, the controller parameters are independent of the sampling interval, allowing it to be designed without any a-priori knowledge of the sampling sequence. Lastly, a simplified and scalable implementation whose dimension is independent of the number of agents, assuming local measurement of the agents' own states, is proposed.

16:05–16:25

*The $k$-Comparison Principle*

**Omri Dalin** (EE@TAU; supervisor: M. Margaliot)

**Abstract:**

The comparison principle allows to bound the trajectories of a dynamical system using those of another, and potentially simpler, system which is cooperative. Here, we use the theory of $k$-compound matrices to generalize this to a $k$-comparison principle. This bounds $k$-dimensional bodies that evolve according to a dynamical system using $k$-dimensional bodies that evolve according to another, and potentially simpler, system which is $k$-cooperative.

16:25–16:45

*Designing Controllers for Non-cooperative Interactions with Multiple Objectives: A New Game-Theoretic Approach*

**Shimon Regev** (ME@BGU; supervisors: S. Arogeti & A. Elyasaf)

**Abstract:**

Designing controllers for non-cooperative interactions has an inherent uncertainty that may require robust controllers. The problem gets more complicated when considering multiple objectives with no a priory objectives weighting. We propose a game-theoretic approach for optimizing performances of controllers that interact with other controllers, considering multiple objectives per controller. Our approach assumes rational control-designers with known multiple objectives and performance functions, but no prior knowledge of players' weighting of multiple objectives. We model the problem as a multi-objective game and utilize the common knowledge of rationality and game properties to search for a reduced set of rationalizable controllers. To handle large search domains, we employ evolutionary algorithms to find an approximation of the set of rational controllers. The proposed approach allows reducing the inherent uncertainty of the multi-objective non-cooperative interaction, by squeezing the knowledge of the interaction, including the rationality of the players.