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Book of Abstracts

Implementation of Minimal Feedback CPG Controller for Dynamic Walking Using Series Elastic Actuation

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Dynamic walking refers to gaits that exploit the natural dynamics of the body and limbs, thus being more energy efficient as shown in [7]. In a dynamic gait the body actually 'falls' forward at every step and static equilibrium does not have to be monitored.

A minimal feedback CPG based controller has been previously developed in our lab to control dynamic walking for legged robots [1] [2]. The design is inspired by the study of the role of GPGs in animal locomotion [3][4][5]. In biological CPGs, a network of neurons acts as coupled oscillators that produces a periodic electric signal sent to the muscles and generates dynamic locomotion [6]. These signals were shaped by years of evolution for the needs of the specific animal. In our control algorithm, we use a CPG to produce a periodic set of torque pulses applied to the hip and ankle motors. The optimized control values were obtained by a genetic algorithm that was tuned to determine the torque pulses for either the fastest, the most energy efficient, or the fastest converging gait.

A prototype was designed and built to demonstrate the CPG controller on a compass biped robot. The implementation includes series elastic actuation (SEA) as introduced in [8], which facilitates the control of the applied torque, while exploiting the natural dynamics of the system and providing inherent compliance.

The implementation was based on parametric system identification and system validation using sine-sweep methods, low-level motor control using PD or LQR control and a state observer based on pole-placement or Kalman filter. The talk will describe the detailed design of the SEA system, compare the alternative control methods, and present the successful walking performance.

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Vehicle Platoon Formation Using Interpolating Control

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Automatic platooning of vehicles on freeways has potential to increase traffic throughput. In this talk, a recently introduced control design approach known as interpolating control (also known as improved vertex control) is presented for the task of forming vehicle platoons. The objective is to regulate the vehicles' speeds and the spacing between the vehicles, from their initial conditions into a shared consensus. A discrete state space formulation, with state and control constraints, is used to model the system, and the interpolating control approach is implemented and compared with other methods such as MPC. Simulation results suggest that the interpolating control approach can serve as an alternative to the MPC approach, for the task of platooning, especially when designing robust controllers for systems with model parameter uncertainty. In addition, experiments conducted on mobile robots equipped with wireless communication modules validate the suggested approach.

Vision-Based Formation Control of Autonomous Robots Using Multi-View Geometry

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In the last two decades, cooperative autonomous robots have been used increasingly in a variety of civilian and military applications. These applications include, for example- search and rescue, law enforcement, environmental mapping. In order to perform these tasks autonomously and efficiently, localization of the robots should be known or estimated and formation must be controlled. It is commonly assumed that the vehicles are localized - an assumption that is invalid in GPS deprived environments, such as when operating indoors, underwater and in space. Therefore, in such cases, two problems should be solved simultaneously – localization and formation control.

Two common vision-based formation control methods are leader-follower and motion capture systems. Both of the methods rely on direct observations of the relative pose (position and orientation). The former relies on measurements such as range measurement, IMU (inertial measurement until) etc. and a single camera which observes the leader and estimates the relative pose between them. The latter requires a predefined infrastructure of cameras mounted in a known environment where the cameras observe the robots and provide measurements of the relative pose between themselves. These methods along others are based on a direct line of sight either between the members of the group or between the mounted camera to the robots and therefore they are not applicable when a direct line of sight requirement is hard to satisfy.

In order to overcome those drawbacks the robots can use indirect measurements in order to perform localization, i.e., they can estimate their relative pose by observing the same scene. Estimating the relative pose using indirect measurements requires having a map of the environment. However, in the case the map is unavailable or imprecise, the robots need to perform simultaneous localization and mapping (SLAM), a well-known problem in robotics.

In order to avoid the need for direct line of sight (LOS) between the robots cameras will be aimed towards objects of interest. Non line-of-sight (NLOS) localization methods have been investigated in recent years [1, 2, 3]. These works achieve localization by matching image features and either formulating projection equations that involve mutually observed 3D points [2, 3], or algebraically eliminate the latter and use multiple view geometry constraints instead [2]. In this research we build upon the above approaches and investigate the usage of indirect multi-robot constraints also for formation keeping, which has not been explored thus far. This concept is expected to allow a group of cooperating robots to maintain a desired formation also in absence of direct LOS between the robots.

We will also explore how to determine the best formation online. While existing approaches typically assume the desired robot formation is given or externally determined, different formation geometries yield different localization performance. Consequently, we will address the question how to dynamically change, or adjust, the formation as a function of the observed scene such that localization accuracy is maximized. One direction that we will explore is to determine the optimal formation by optimizing an information-theoretic objective function, which involves the mentioned indirect multi-robot constraints (either projection equations or multiple view geometry constraints).

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Theoretical and Experimental Investigation of the Twistcar Vehicle's Dynamics

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Twistcar is a plastic ride-on toy car which consists of two axles: main axle and steering wheel axle. It is propelled by applying cyclical changes in the steering wheel angle, and its dynamics is governed by a combination of momentum balance and non-holonomic constraints of no-slip at the wheels' axles.

In this work we have investigated dynamics and control aspects of no-slip motion using analytical and numerical methods. First, we formulated the equations of motion using Lagrange's method for systems with non-holonomic constraints, under torque or angle input. We simulated the dynamical system numerically using MATLAB in order to obtain basic understanding of the dynamic behavior. Next, we used the constraints with some algebraic manipulations in order to obtain a reduced system that can be analytically investigated. Finally, we obtained analytical expressions for the vehicle's motion dynamics using Perturbation Expansion method.

Moreover, we built a VEX robotic model of the Twistcar, which was used to verify and demonstrate some of the theoretical results.

Distance-Based Formation Tracking Control

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Formation control of multi-robot networks is an area of ongoing research in control systems. In recent years, there has been an increasing number of contributions dealing with the control of multiple agent formations. A closely related problem is formation tracking where the objective is to find a control scheme that allow multiple robots to maintain some given formation while executing additional tasks such as velocity tracking or leader following.

The theory of rigidity has emerged as the correct mathematical foundation for defining distance-constrained formations and proving that distance-constrained formation control strategies are stabilizing As a first contribution of our work, we provide a local stability proof by deriving the dynamics of the formation error and employing Lyapunov's indirect method.

Although some earlier related studies addressed the issues of analyzing the decentralized control laws embedded in the agents for distance control, fewer can be found answering the question of tracking an input reference of only one of the agents.

In our work, we investigate the problem of controlling a group of mobile agents with single integrator dynamics to track a reference velocity of a single leader. When one of the agents is assigned with an external velocity command, the objective is to preserve the correct distance-constrained formation by the other agents while following the leader. In the absence of any additional control action, the standard rigidity based formation stabilization solutions will exhibit a steady-state formation error. Our approach is to combine gradient control laws with a proportional (P) gain controller to reduce this steady-state error. We show that such a scheme preserves the stability properties of the formation error dynamics as well as properties of the networked system's centroid. We also reveal more interesting relations between the upper bound of the steady state error and the graph properties. This scheme has many advantages, including a simple and distributed implementation and no need for virtual leaders.

Appropriately, in order to completely eliminate the steady-state formation error, we augment the gradient based formation controller with a proportional and integral (PI) control on the formation error. We show that such a scheme preserves the stability properties of the formation error dynamics while ensuring a zero steady-state formation error.

Time Optimal Trajectory Planning with Feedforward and Friction Compensation

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The problem of time-optimal trajectory design for high performance point-to-point positioning system under state and control constraints is considered. The proposed solution takes into account Coulomb and viscous friction. A particular structure for the trajectory is postulated, and conditions for its optimality are proven using the Pontryagin Maximum Principle. The explicit solution for the co-states is found. It is shown that one of the co-states contain jumps, together with two singular arcs. Results for a real-life implementation on a nano-positioning X-Y stage are shown.

The optimal minimum-time problem with bounded states and with friction compensation was, to the best of our knowledge, unsolved until now. It may be part of the solution also for more complicated positioning problems, like two degrees-of-freedom X-Y movements, dual stage systems and a part of pre/post actuation techniques.

Analytical Observability Analysis of Vehicle Constraints and Vision Aided Navigation

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Navigation applications have been in common use for many years now, ranging from door to door vehicle navigation, automated processes, and mapping technologies. The most common form of navigation nowadays, is via point positioning using global navigation satellite system (GNSS) receivers. However, this method requires a clear line of sight to at least four satellites, which can be negated in urban settings, underground or indoors.

Inertial navigation systems (INS) have an advantage over GNSS based ones, as they rely on measurements derived from the platform itself, and not external satellites. However, inherent biases in the inertial sensors cause the navigation solution to drift overtime. To overcome this problem, aiding schemes have been proposed where INS and GNSS are combined. This has the same constraints as a standalone GNSS solution and therefore inapplicable in the settings described above.

In order to reduce inertial navigation drift, vehicle constraints have been gaining increased popularity as a means to mitigate drift of inertial navigation systems in GNSS deprived settings. Another useful method, which is very popular for mapping technologies is simultaneous localization and mapping, which also provides a three dimensional model of the surroundings. While useful, such constraints cannot compensate for the drift of all state variables in the navigation solution. To study which variables are affected, empirical analyses under typical scenarios are commonly performed, however, no insight is provided into the inner effects amongst error states.

Here we develop analytical observability terms which evaluate the contribution of vehicle constraint measurements to the solution and determines which error states or a linear combination of them are unobservable. Observability analysis has been mostly directed thus far at GNSS/INS aiding and is generally performed in a binary manner.

In this context this we fill this gap by deriving analytical terms for the unobservable subspace of the body velocity constraint, which is already utilized in urban driving scenarios. In addition, an approach to mitigate inertial drift combining simultaneous localization and mapping (SLAM) and the body velocity constraint is proposed. For this combination, analytical terms of the unobservable subspace are derived as well. In this approach we show that it provides full error state observability for most urban driving schemes. This provides a suitable solution for urban navigation schemes.

The analytical terms derived in this research are verified via a numerical analysis of urban driving scenarios using a degree of observability approach. This approach is normalized as compared to a regular covariance analysis, and therefore the results are not dependent on the initial accuracies of the error states.

The Ribosome Flow Model on a Ring

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The asymmetric simple exclusion process (ASEP) is an important model from statistical physics describing particles that hop randomly from one site to the next along an ordered lattice of sites, but only if the next site is empty. ASEP has been used to model and analyze numerous multiagent systems with local interactions including the flow of ribosomes along the mRNA strand.

In ASEP with periodic boundary conditions a particle that hops from the last site returns to the first one. The mean field approximation of this model is referred to as the *ribosome flow model on a ring* (RFMR). The RFMR may be used to model both synthetic and endogenous gene expression regimes.

We analyze the RFMR using the theory of monotone dynamical systems. We show that it admits a continuum of equilibrium points and that every trajectory converges to an equilibrium point. Furthermore, we show that it entrains to periodic transition rates between the sites. We describe the implications of the analysis results to understanding and engineering cyclic mRNA translation in-vitro and in-vivo.

All in One – Fractional Order Impedance Matching, Delay Compensation and Repetitive Control of the Damped Wave Equation

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In mechanics, the wave equation describes vibration of energy conservative, continuous flexible systems that have no resistance to bending, such as strings or rods. These systems are employed in various engineering applications, including space structures and deep well drilling for oil and gas exploration. In practice, however, the free vibration decays with time due to the presence of damping from different sources. The damping is commonly represented by a vibration on viscous foundation, and is modeled by a linear dissipative term, producing the damped wave equation.

The flexibility, however, may carry some disadvantages. Since flexible systems are light weight, their resonances begin at low frequencies, causing even slow tracking maneuvers or disturbance signals to excite undesired vibrations. Although overcome by the damping in steady state, these vibrations might violate some performance requirements, and therefore need to be suppressed. While passive rigidization will simply result in heavier structures, the alternative is active control. Partial differential equations are not a standard starting point for control algorithms. A common approach is transforming the problem into the familiar and well explored realm of finite dimension linear systems. However, insight into the system response and properties, such as delays, is lost and cannot be utilized for controller design.

In this work a different modeling and, consequently, a control approach is presented. The model includes fractional order transfer functions, which are shown to represent the special manner of wave propagation in the system. Its building blocks, exponents of non-linear functions of '*s*', may be considered as non-pure delays, i.e. they not only shift a wave but also distort its shape. The distortion character is according to modified Bessel functions of the first kind.

Based on this model, a non-collocated setting of boundary actuation and measurement was constructed. In the first stage, the controller stops the reflection of waves from the system boundaries. Mathematically, this is done by eliminating the delay exponent from the characteristic equation. Physically, the controller matches the impedance of the boundary to that of the entire structure. The resulting transfer function is given by a single non-pure delay exponent, which is transformed to a pure delay by a specially designed filter. These controllers are of fractional order and are implemented by dedicated approximations. Although the impedance matching stabilizes the velocity system, it does not provide a complete steady state rejection of persistent disturbances.

The latter becomes the role of the second stage controller, the basic structure of which is a standard internal model dead time compensator. The result is a pure delay velocity tracking system and repetitive control regulation, which means that harmonic disturbances at certain frequencies (including constant signals) are annihilated. It is shown that by introducing a feedback channel component, the controller zeros can be made of any order and thus rejecting, e.g., a polynomial disturbance of any order.

The third stage controls the structures position. The resulting unstable (due to the integration) plant is controlled by Smith predictor. Persistent disturbances are rejected in the position loop as well due to the second stage controller.

Minimizing the Maximal Characteristic Frequency of a Linear Chain

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We consider a linear chain of masses, each coupled to its two nearest neighbors by elastic springs. The maximal characteristic frequency of the chain is a strictly convex function of parameters that are suitable functions of the masses and spring elasticities. Minimizing the maximal characteristic frequency under an affine constraint on these parameters is thus a convex optimization problem. For a homogenous affine constraint, we prove that the mass and elasticity values that minimize the maximal characteristic frequency have a special structure. They are symmetric with respect to the middle of the chain, and as we move towards the center of the chain, the optimal masses increase, whereas the optimal spring elasticities decrease. Intuitively speaking, in order to minimize the maximal characteristic frequency we need to "fix" the center of the chain, by increasing [decreasing] the masses [spring elasticities] there. We describe an application of these results to a model from systems biology called the ribosome flow model.

A Time-Delay Approach for Decentralized Networked Control of Systems with Local Networks

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This talk is devoted to the time-delay approach to large-scale networked control systems (NCSs) with multiple local communication networks connecting sensors, controllers and actuators. The communication delays are allowed to be greater than the sampling intervals.

The local networks operate asynchronously and independently of each other in the presence of variable sampling intervals, transmission delays and scheduling protocols (from sensors to controllers).

A novel Lyapunov-Krasovskii method is presented for the exponential stability analysis of the closed-loop large-scale system. In the case of one controller and two networks (from sensors to controllers and from controllers to actuators) our results lead to simplified conditions in terms of reduced-order linear matrix inequalities (LMIs) comparatively to the recent results in the framework of time-delay systems. Polytopic type uncertainties in the system model can be easily included in the analysis. Numerical examples from the literature illustrate the efficiency of the results.

New Stability and Exact Observability Conditions for Semilinear Multidimensional Wave Equations

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The problem of estimating the initial state of 1-D wave equation with globally Lipschitz nonlinearity from boundary measurements on a finite interval was solved recently by using a sequence of forward and backward observers, and deriving the upper bound for exact observability time in terms of Linear Matrix Inequalities.

In the present talk, for systems with locally Lipschitz nonlinearities we derive an estimate on the region of initial conditions that are guaranteed to be uniquely recovered from the measurements for 1-D wave equation. Furthermore, we generalize the minimal observability time results to n-D wave equation on a unit hypercube with globally Lipschitz nonlinearity. This extension includes new LMI-based exponential stability conditions for n-D wave equation, as well as an upper bound on the minimum exact observability time in terms of finite dimensional LMIs (regardless of the number of dimensions).

The generalization to n-D case preserves the theoretic minimal observability time obtained in the 1-D case, and produces upper bounds on the minimal observability time for n>1. The efficiency of the results is illustrated by numerical examples.

Wave-Number Pair Efficient Control of Plane Poiseuille Flow Transition

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Prevention of transition from laminar to turbulent flow can provide significant drag savings in a range of applications. Transition in plane Poiseuille flow is important as a model problem for other more geometrically complex flows. It provides a sort of proving ground for transition control strategies with relatively straightforward implementation in direct numerical simulation. While the linearized dynamics of laminar plane Poiseuille flow decouple by wave-number pair by applying a Fourier transform in the streamwise and spanwise directions, efforts at implementing transition control in simulation have employed either full state reconstruction or control over a wide range of wave-numbers present in simulation. Perhaps more significantly, both the sensors and actuators are typically employed with the same resolution as the simulation grid. Both of these issues are problematic when looking towards real-time physical implementation.

Our previous work has addressed the state estimation of perturbations to plane Poiseuille flow using sparsely distributed sensors. Underlying said work is the presumption that transition thresholds can be improved nearly as effectively using control of only a narrow range of wave-number pairs as with a fuller range of pairs. Our present work examines to what degree that assumption holds. The transition threshold improvement of full-state feedback LQG controllers is evaluated using wave-number pair ranges of various sizes to determine what range of pairs must be controlled to achieve a particular performance specification, enabling the eventual use of sparsely distributed actuators. The transition threshold improvement performance is found to plateau outside a narrow range of wave-number pairs; controlling additional pairs yields no performance improvement. This plateau effect is attributable to a combination of both decreasing growth and amplification of disturbances and decreasing controllability with increasing wave-number.

Symmetries and Gaits for Purcell's Three-Link Microswimmer Model

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Robotic locomotion typically involves using gaits — periodic changes of kinematic shape, which induce net motion of the body in a desired direction. An example is robotic microswimmers, which are inspired by motion of swimming microorganisms. One of the most famous theoretical models of a microswimmer is Purcell's planar three-link swimmer, whose structure possesses two axes of symmetry. Several works analyzed gaits for robotic three-link systems based on body-fixed velocity integrals. Using this approach, finite motion in desired directions can only be obtained approximately. In this work we propose gaits which are based on analysis of the system's structural symmetries, and generate exact motion along principal directions without net rotation. Another gait that produces almost pure rotation is presented, and bounds on the small-amplitude residual translation are obtained by using perturbation expansion. Next, the theory is extended to more realistic swimmers which have only one symmetry axis. Gaits for such swimmers which generate net translation are proposed, and their small-amplitude motion is analyzed using perturbation expansion. The theoretical results are demonstrated by using numerical simulations and conducting controlled motion experiments with a robotic macro-swimmer prototype in a highly viscous fluid.

Modeling and Control of a Hexacopter UAV with a Rotating Seesaw

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Multicopters are, in general, under actuated systems with only four independent controlled degrees of freedom (DOFs). The x and y position coordinates (with respect to an inertial frame) are coupled with the roll and pitch angles. In order to overcome the under actuated limitation and to achieve independent control of all six DOFs, a change in the multicopter platform needs to be implemented. Different solutions on how to improve the platform and actuate the multicopter have been proposed in literature. Most of the solutions suggest the tilting rotors concept in which the rotation is performed by additional (tilting) motors; the down side of adding these motors is the additional weight, without increasing the lifting power. We suggest a thrust tilting solution without this mentioned down side.

In this research we develop a novel multicopter structure. The platform gives the aerial vehicle the ability to control five independent DOFs (e.g., position, heading and pitch angle) and the concept can be extended to the control of all six DOFs.

The present developed platform is a hexacopter (i.e., it uses six lifting propellers), where four propellers are attached to the vehicle body and another two are attached to a seesaw. The seesaw is connected to the main body in the center of mass and can rotate along one axis of the body frame, which consequently adds the fifth controlled DOF (of the main body). This design makes the aerial vehicle more maneuverable without adding actuators that are not directly contributing to the total lifting power. The seesaw angle (with respect to the main body) is measured by an optical encoder, installed on the seesaw hinge.

The research deals with the development of the new platform, its dynamic modeling and non-linear control. Five DOFs trajectory tracking capabilities are demonstrated using numerical simulations.

A Dynamic Model of Vehicle During Four-Wheel and Two-Wheel Roll Over, with Steering and Braking Anti-Roll Over Actuation

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The rollover propensity of a vehicle is a major cause of vehicle instability, both on - and off – road. There are three fundamental factors that impact the possibility of rollover: vehicle geometry, tire−ground interaction, and vehicle dynamics. Anti-roll action must be taken immediately as the roll-over danger is detected.

In this work a new non-linear vehicle model for roll-over is developed and presented. The model describes the three different wheel contact modes: 1) all four wheels at the ground; 2) left tip-up where only the two left wheels remain in contact with the ground; 3) right tip-up. Models 2 and 3 are pre-cursors to possible roll-over. A new and better model-based roll-over predictor was developed that works also for modes 2 and 3, in contrast to the conventional one called LTR (Load Transfer Ratio) suggested by Odenthal at al. at *Non-linear Steering and Braking Control for Vehicle Roll-over Avoidance* , ECC 1999.

The roll-over avoidance control algorithm uses steering and brakes as control variables. Quantitative Feedback Theory (QFT) was used to design a robust roll-over avoidance control algorithm. The algorithm was tested first in simulation and then will be validated experimentally on an actual autonomous unmanned ground vehicle (UGV) driven in the Cooperative Autonomous System (CASy) lab.

Comparison of Nonlinear State Estimators: Methodology and Application

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State estimation in nonlinear systems is a well explored but still challenging engineering task, which usually requires the use of some sub-optimal filer. A variety of such filters have been developed over the years. A particular challenge is the choice of the appropriate model and filter for a given task. A first difficulty is that different solutions may be preferable under different operating conditions. A second difficulty in comparing filter performance is that several and possibly contradictory performance measures may be involved, such as the filter accuracy vs. its speed (or bandwidth). Furthermore, each filter has at least one tuning parameter which controls its performance and possible tradeoff between performance criteria. Consequently, there does not seem to be a uniform and agreed-upon paradigm for comparing filters for nonlinear state estimation tasks.

In this work, we propose a structured methodology for comparing filter performance and apply it to the problem of state estimation of a target performing a 2-D barrel roll maneuver. The proposed approach is based on the notion of the Pareto front. We focus on two performance measures, the state RMS estimation error versus the settling time. For each filter we plot the Pareto front (i.e., the set of undominated points in the performance space) that is obtained as the filter tuning parameters are varied over their useful range. The filters are ranked by comparing the plotted Pareto fronts.

We apply this methodology to the problem of state estimation of a target performing a 2-D barrel roll maneuver with constant unknown angular velocity. The following filters are compared in this study: EKF, IEKF, SDDRE based filter, ISDDRE filter, UKF and Θ-D filter. A single tuning parameter which is the driving noise level in the system model is used in all cases. Furthermore, sensitivity studies with respect to different parameters and assumptions about the target maneuver were performed.

Sensory Adaptation for Control based on Point-Process Observations Using Gaussian Approximations

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Biological agents acting in the natural world are required to implement effective control policies based on sensory observations from spiking neurons. The firing process of these neurons is well described as a point process that encodes the external state. It has been shown experimentally that in learning to solve such problems, agents adapt not only their control policy but also the encoding of sensory information. Previous work on control based on point-process observations has derived optimal control policies under strict assumptions on the point-process statistics, which guarantee that the posterior state distribution is Gaussian and that the certainty-equivalence based control policy is optimal. In the context of neural encoding, these assumptions correspond to the biologically unrealistic proposition that the neurons' preferred locations uniformly cover the state space. Within this framework, it was shown that the optimal encoding depends on the details of the control task, despite the fact that the separation principle holds for a fixed encoding. In this work, we consider a similar model where neurons' preferred locations are themselves sampled from some distribution. When this distribution is Gaussian, we can approximate the posterior distribution of the state as Gaussian, using the technique of Assumed Density Filtering (ADF). This allows us to derive filtering equations for the approximate posterior in closed form. We explore the performance of the (suboptimal) certainty-equivalent control policy using this approximate posterior and the optimal parameters of the neural encoding. Consistently with biological experiments, our results demonstrate that sensory adaptation is beneficial for control and that sensory adaptation for control differs from sensory adaptation for state estimation.

Probabilistic Data Association in the Presence of Unobserved Areas

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Modern tracking systems need to be capable of estimating the distribution of targets in a surveyed scene while coping with a variety of uncertainties, such as unknown number of targets, unknown target motion models, missed detections and clutter (false measurements). An even more challenging tracking scenario may occur when trying to track targets in a scene that includes unobserved areas. Such situations may arise in urban environments including man-made occlusions [e.g., buildings blocking the field of view (FOV)], or in environments involving topographic constraints (e.g., mountains blocking the FOV). In such situations the tracking system needs to be able to reason about the target motion even without information that is not readily accessible, when the target resides in unobserved regions of the environment.

In this research we address the problem of tracking a single, non-maneuvering target, moving in a scene containing unobserved areas that are a priori known. A modified probabilistic data association (PDA) filter is developed, that can take into account pre-defined unobserved areas, in addition to target-originated measurements, missed detections, and clutter. The modification is based on the "negative information" concept. Expected, but actually missing, measurements in a scene that contains unobserved areas may be considered as useful information that can be exploited by the tracking system. In order to use this kind of information it is formulated as fictitious measurements that embody the essence of the negative information. In our case a fictitious measurement, and its associated measurement noise covariance, are formulated based on the unobserved areas geometry. This measurement is used to update the target estimated state and error covariance by using a regular Kalman filter approach within the standard PDA framework.

The performance of the modified PDA filter is demonstrated via numerical simulations. Track continuity is demonstrated even in unobserved areas, with controlled growth of the standard deviation, allowing robust tracking when the target becomes detectable again.

Energy-Optimal Precise Wafer Stage Positioning: Equivalence with Minimal Time Optimality

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The problem of precise positioning is an important subject in the field of control in particular in the electronic industry in which wafer stage positioning is critical for processes including wafer diameter of 450 mm and others. The optimal trajectories and controls are governed by the objective function and constraints of reality. Solutions using an S-curve profile are valid but lack proof of criteria optimality. A novel way of minimum-time feed forward design is found in the Pontryagin Maximum principle.

A model with three state variables (displacement, velocity and driving force) is considered with Coulomb and viscous friction and with constraints on the driving force, velocity and jerk. Two different objective functions (time or energy) are considered. First the minimal time objective function is solved. The minimal time found is used as the time constraint in the minimal energy objective function. We find that the trajectories are the same in both cases according to the theoretical considerations, and also as a result of the numerical optimization. The results can be understood intuitively and can be explained to people outside the field of optimal control using simple terms. Using this understanding can be important for optimal trajectory design for stage positioning in the electronic wafer industry.

Region of Attraction Estimation for Periodically Actuated Compass Biped

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The compass biped model, also known as ’the simplest walking model’, is a minimalistic hybrid-dynamic model, widely used to study dynamic bipedal locomotion. The model is known to exhibit stable limit cycles on downward inclined slopes without actuation. It was shown previously in our lab [1] that periodic actuation in open loop can result in stable limit cycles on a wide range of slopes. In this work we try to explore global properties of stability of the periodically actuated compass biped. Namely we want to find subsets of the region of attraction (ROA).

We use a method developed by I.R Manchester in [2] for estimating the ROA of limit cycles in hybrid systems. The method involves transforming the dynamics of the system into a coordinate frame transverse to the limit cycle, and verifying subsets of the ROA by finding a Lyapunov function. The provable subset of the ROA is then maximized trough an iterative optimization Procedure.

In my presentation I will outline the method and apply it on an illustrative example.

References

[1] A. Evstrachin J.Spitz and M.Zacksenhouse. Minimal feedback to a rhythm generator improves the robustness to slope variations of a compass biped. Submitted to Bioinspiration and Biomimetics, 2015.
[2] Ian R Manchester. Transverse Dynamics and Regions of Stability for Nonlinear Hybrid Limit Cycles.

Real-Time Power Sharing with Low-Rank Coordination

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Recent years have witnessed a growing demand for electricity, which has led to an increased generation of energy by distributed energy resources (DERs). The use of small DERs, located next to the customers, reduces the amount of energy lost in transmitting electricity, although a grid composed of DERs is more sensitive to disturbances. The grid is required to supply customers demand by coordinating a large number of DERs, while maintaining efficient energy production. The resulting real-time power sharing is an open challenge for optimal dynamic control as traditional, fully-coordinated, approaches produce controllers, which demand complex and expensive communication infrastructures.

Due to the complexity of such grids, scalable solutions become a must. This work is a step toward an efficient real-time power sharing of distributed generators. We propose an approach to control a few groups of homogeneous generators, where all generators in the same group have the identical dynamics and might be thought of as a micro-grid. The goal is to minimize the overall cost of fuel over some period of time, while tracking a power reference signal. We cast this problem as an H2 constrained optimization problem and derive its solution. The resulting controller is highly scalable, both computationally and implementationally. In particular, the only non-local information required is the total power supplied to the grid.