Ph.D. subject: Connected and Proactive Navigation of mobile robots in the Industry of the Future

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Context

Nokia and INRIA are collaborating in the framework of Nokia Bell Labs (Inria common lab) and setting up three main challenges: Distributed learning over 6G, AI-based smart network management, and Network aware industrial applications.

Nokia Bell Labs is the world-renowned research arm of Nokia, having invented many of the foundational technologies that underpin information and communications networks and all digital devices and systems. This research has produced nine Nobel Prizes, five Turing Awards, and numerous other awards.

Within Nokia Bell Labs, ISE Lab (Integrated Solutions and Experiences) is responsible for researching, designing, building, integrating, and delivering disruptive and best-in-class solutions and experiences that leverage the Bell Labs Research assets and innovations across multiple complex technology areas. Our team comprises researchers and engineers with backgrounds, experience, and interests in distributed and networked control of autonomous robots.

ACENTAURI is a robotic team located in Sophia Antipolis that studies and develop intelligent, autonomous and mobile robots that collaborate between them to achieve challenging tasks in dynamic environments. The team tackle perception, decision and control problems for multi-robot collaboration by proposing an original hybrid model-driven/data driven approach to artificial intelligence and by studying efficient optimisation algorithms. The team focus on robotic applications like environment monitoring and transportation of people and goods. In these applications, several robots will share multi-sensor information eventually coming from infrastructure. The effectiveness of the proposed approaches are demonstrated on real robotic systems like cars AGVs and UAVs together with industrial partners. Since, last five years the team members are focusing on autonomous navigation in human populated environment, exploring reactive and cooperative navigation while targeting to develop the concept of ***proactive navigation***.

Problem statement

Navigating autonomous robots in the operational environment of the Industry of the future poses significant challenges due to the presence of humans, diverse autonomous devices (such as robots), and machines operated by humans (like forklifts), all sharing the same space. In this research, our primary objective is to present a unified navigation and control model and framework for autonomous robots, enabling them to navigate efficiently in the presence of diverse types of moving objects.

Several studies have been conducted on robot navigation in human-populated environments, targeting applications such as supermarket floor cleaning, package transportation and delivery, and orientation guidance in historical centers, museums, fairs, and similar settings. Achieving socially acceptable and safe autonomous navigation in such environments requires ***estimation of the behavior of actors*** (including humans, moving obstacles, and other robots), ***computing real-time control while ensuring safety***, and ***performing proactive navigation*** (i.e., computing actions that are compatible and acceptable to humans while avoiding the Freezing Robot Problem [1]).

To successfully navigate robots in human-populated environments, understanding human behavior is likely the most complex issue that must be addressed. Firstly, understanding Human to Human interactions is essential. In [2], the author presents a categorization of the surrounding space into different types (Intimate, Personal, Social, and Public) from which proxemics were defined for Human to Human interactions (H2H). In [3], the ***Social Force Model*** (SFM) is described, which provides the model of pedestrian motion as a result of the application of a set of forces called" ***social forces***". Social forces are exerted on the pedestrian from different sources, the force driving the pedestrian toward a destination, forces imposed by other pedestrians, and forces from the obstacles around the pedestrian.

As of the present day, the SFM technique continues to be the most extensively used method in both academia and practical applications. Several versions of this model have been developed, including the Extended Social Force Model (ESFM) [4], the Headed Social Force Model (HSFM) [5], and the Collision Prediction Extension of Social Force Model (CPESFM) [6]. All these extensions consider interactions with Humans (H2H), Obstacles (H2O), Robots (H2R), and, more generally, everything (H2X).

Based on the H2X Social Force model, the SPACiSS simulator [7] was developed at Inria. SPACiSS was utilized in the recent research on pedestrian-friendly and proactive navigation for autonomous vehicles operating in a shared, open space with pedestrians [8]. The knowledge accumulated in H2X interaction modeling can offer valuable insights for developing Robot to everything (R2X) models. Incorporating H2X principles into R2X can lead to a more natural understanding and acceptance by humans, allowing the robots to behave more human-like in dynamic environments.

Despite significant progress, accurately predicting human intentions in specific settings remains challenging. SFM-based models, which are commonly used for such predictions, have a limitation due to their reliance on hand-crafted functions and models, which may restrict their predictability level. There is a growing interest in integrating data-driven approaches to overcome this limitation and improve the effectiveness of SFM-based models in understanding human behavior and interactions, especially in complex and diverse environments. Combining SFM-based models with data-driven methods, which we will be exploring in this collaboration, makes it possible to enhance the overall predictability of these models, offering a potential solution to the challenge of predicting human intentions more accurately.

Another alternative approach being explored is to learn the social interaction of people in a crowdy environment by utilizing various learning techniques and tools. For instance, new data-driven techniques have been used in crowd modeling and simulation [9]. The Deep Social Force Model has also been developed [10, 11] and produced promising results. An emerging trend involves addressing the combination of data-driven and model-driven techniques [12].

Recently, ACENTAURI has started to work on a further extension of the SFM by defining the ***Universal Social Force Model*** (USFM) that the robot controller can use for autonomous navigation. In this Ph.D. subject, we intend to explore new hybrid techniques mixing data-driven and model-driven techniques and deploy this model in the industrial environment. This model USFM can be used either for H2X interaction modeling, but also for R2X interaction modeling, making the robot behavior (mainly robot motion) more sociable and liable in human and other autonomous or human-operated devices populated environments.

Computing real-time control while ensuring safety over a fixed time horizon is a challenging task. One approach to address this challenge is Model Predictive Control (MPC), which involves computing optimal control while anticipating future events within a time horizon. However, state-of-the-art works often fail to mention the computational efficiency of MPC in real-time applications. A significant drawback of using an MPC controller is that it requires considerable time and computational resources to perform an online optimization problem at each time step, which limits its application in real-world scenarios [13].

Machine Learning (ML) techniques have been proven to be adequate to improve the performance of MPC controllers by providing good prediction models from data, reducing the problem size and therefore improving the optimization performance, and selecting the best MPC parameters. Control parametrization is an effective solution [14][15], significantly reducing the number of control variables in the optimization problem while minimizing performance loss. Recent works have applied control parametrization on real-time simple systems [16] and dynamic vehicles [13]. The main goal of control input parametrization is to reduce the dimension of the complexity by using a parametrized control mapping. In that way, the number of degrees of freedom of the control is greatly decreased, making it possible to use a longer horizon of prediction for the short term planning in MPC.

Recently, ACENTAURI has worked on a new control input parametrization [17] that outperforms previous ones and allows for an efficient real-time implementation on a real robot in complex scenarios. The main idea is the use of Radial basis function for the parametrization. In this Ph.D. subject, we will explore this idea by looking at data-driven techniques to solve this problem.

Nokia and ACENTAURI will work on ***connected autonomous Robot in an industrial environment***. Figure 1 presents the targeted system to be studied:

The blocks in yellow are the focus of this proposal. The cloud (in Figure 1) implements the application level using an orchestrator, which defines subgoals, navigation policies, potential virtual robot/pedestrian, and virtual barriers. Localization of the robot and dynamic agents in the environment must be provided using the sensors installed on the robots or the environmental sensors. The frequency at which this information is required depends on the operational environment of the robot and its speed. The robot (in Figure 1) elaborates on the best control over one horizon of time, considering the local behavior (including humans) detected by embedded sensors in case of connection loss.

The main goals of the Ph.D. will be to finalize the concept of Universal Social Force Model to be used for H2X to R2X interaction modeling, to develop a module to estimate the cooperability of the human and other present autonomous and human-operated devices (a priori, identified and computed in the cloud), to put in place a proactive navigation strategy based on a parametrized nonlinear MPC framework, and to define where computation can be done in the different use cases provided by Nokia. The work's outcome must be validated in the physical

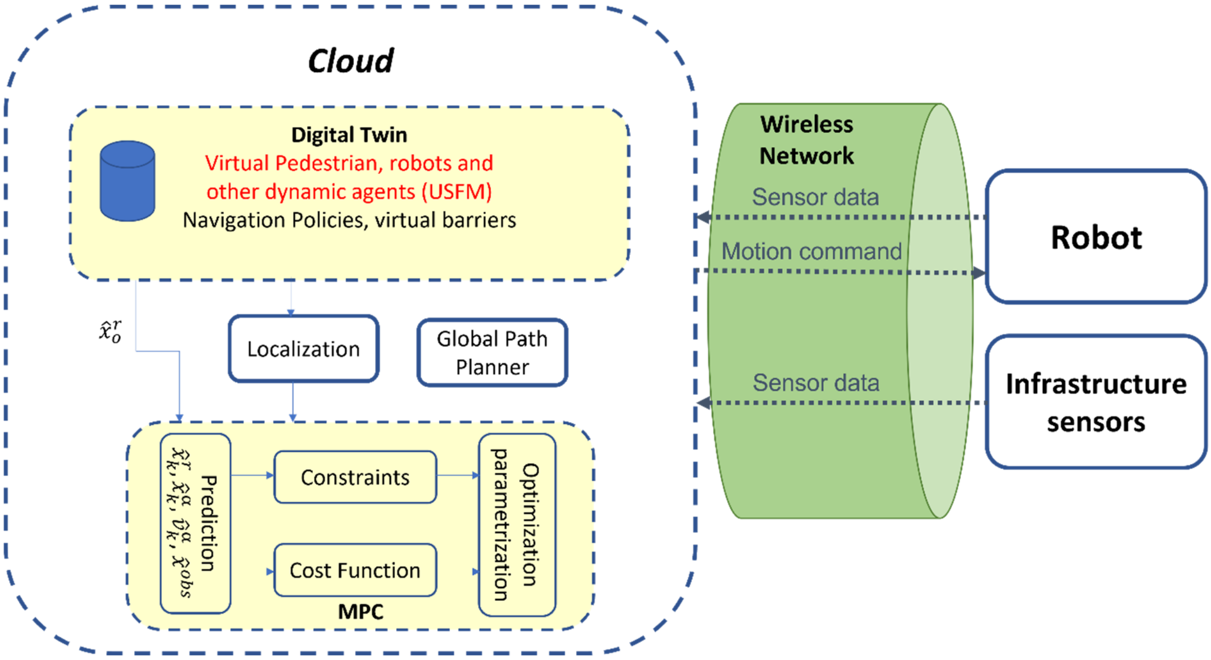

Figure 1: Target architecture of the system

environment and integrated into the navigation stack of Nokia's ROS-based robot system and, more generally, into the navigation stack of a 3rd party robot.

To accurately estimate the behavior of an agent, learning the model automatically from demonstrated living data using Inverse Reinforcement Learning is one option that will be investigated. An example is given in [18] for autonomous driving applications. Another investigation can be to tune parameter's values by using reinforcement learning. In ACENTAURI, we strongly believe that developing hybrid techniques (mixing data-based and knowledge-based techniques) is an important track to be followed. An example is given in [19].

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