Abstract—Robots capable of providing physical assistance to a human partner face a wide area of application scenarios ranging from manufacturing assistance, physical rehabilitation to mobility aids for the elderly. Yet, the physical nature of the coupling present in cooperative manipulation tasks and the uncertain contribution of the human partner make physical robotic assistance a challenging topic of research. In this work, we present our current lines of research addressing the topics of learning, planning and control in the context of physical human-robot interaction. Valuable insights from human-robot experimental studies conducted in rapid prototyping environments are reported as well.

I. INTRODUCTION

Robotic systems able to assist the human partner in physical tasks opens up new application scenarios beyond the well-defined industrial settings, e.g. in the daily-life service and medical domain. The tight physical coupling between the cooperating partners requires instantaneous, predictable and safe decision making to provide smooth and intuitive human-robot interaction. While robotic assistance with a purely reactive behavior to human actions can be considered state-of-the-art, the design of pro-active assistive behavior remains still challenging: it requires fast, goal-directed planning of actions under dynamically changing conditions, understanding of the human partner’s actions, and action taking in awareness of the human’s uncertain feedback.

In this work, we present an overview of our recent works towards autonomous robotic assistance in physical human-robot interaction (pHRI), see Fig. 1 for the overall scheme. The approach to combine incremental learning and feedback planning techniques in pHRI [7] feedback planning techniques in pHRI [1] to exploit the strength of both strategies is presented in Sec. II. Our novel disagreement-aware control concept based on risk-sensitive optimal feedback control [2] [3] is outlined in Sec. III. In Sec. IV, the development and evaluation of a dynamic role allocation scheme [4] is introduced in short. The rapid prototyping environment for pHRI experiments is shown in Sec. V. The paper concludes with Sec. VI.

II. COMPLEMENTARY STRENGTHS OF LEARNING AND PLANNING

Pro-active physical assistance requires goal-directed behavior and therefore remains one of the biggest challenges in pHRI. Goal-directedness can be realized by two conceptually different approaches on motion generation: planning and learning from demonstration. The human partner’s contribution cannot be pre-planned, and thus always deviates from any feed-forward generated motion plan. In this work, we propose and evaluate a feedback-planning approach [1] which is compared to our incremental learning scheme presented in [5]. Furthermore, synergies arising from the fusion of planning and learning techniques are explored under the following conditions:

- plan-based initialization of the learning scheme,
- prediction-based homotopy-blending of planning and learning schemes, and
- cost-based fusion of both strategies.

Our results from a virtual human-robot cooperative task show a superior performance compared to the individual strategies when planning and learning algorithms are combined in synergistic strategies. In addition, both the incremental learning

![Feedback motion planning](image1)  
(a) Feedback motion planning  

![Left-to-right HMM learning](image2)  
(b) Left-to-right HMM learning  

Fig. 2: Motion generation algorithms in 6D ($x_0/y_0$ components) [1]

and the feedback planning scheme are evaluated in proof-of-concept implementations of large-scale cooperative transport tasks on a six-DoF mobile manipulator [1] [5], see Fig. 2.

III. DISAGREEMENT-AWARE ASSISTANCE

Based on the finding that human sensorimotor behavior follows principles known from risk-sensitivity theory, we develop a novel control concept for pro-active physical robotic...
assistance [2]. Intuitive interactive behavior is achieved when considering the uncertain and variable human contribution to the task as process noise in a probabilistic dynamic model. While this approach results in a model-based feed-forward controller relying on past observations, in our recent work [3], we estimate the current level of disagreement to account for unmodelled human variabilities. Results provide evidence for human-adaptive physical assistance integrating both the expected and the current disagreement of the human.

IV. DYNAMIC ALLOCATION OF ROLES

One key-point in pHRI is the mutual understanding of the partner’s input behavior and the negotiation of the physical effort required to accomplish a cooperative task. Humans are known to successfully manage haptic negotiation by a self-organized distribution of the effort. Based on our previous work on the formal analysis of load distributions in a redundant cooperative manipulation task [6], we develop strategies for assigning the task effort while allowing for dynamic role changes of the partners [4]. Human force feedback is utilized and interpreted as an agreement indicator in two different role allocation schemes, namely the

- weighted pro-active role allocation (WPRA), and the
- discrete role allocation (DPRA).

These schemes adjust the robot’s role regarding its effort behavior depending on the human agreement in a continuously blended fashion and a distinguishably discrete three-step fashion respectively. A user study involving large-scale kinesthetic interaction shows a trade-off between subjective and objective performance of the proposed dynamic schemes when compared to a constant role allocation (CRA), with a clear objective advantage of the weighted pro-active role allocation reflected in measures such as completion time and applied effort, cf. Fig. 3.

V. RAPID PROTOTYPING ENVIRONMENT

Physical human-robot interaction requires real-time decision making of the robotic agent due to the inherent physical coupling of cooperative tasks. Successful investigation and development of pHRI-capable robots requires human-in-the-loop experiments conducted in robust, safe and flexible system environments. Integrated learning, planning and control schemes resulting from our research work are shown to be subjectively and objectively evaluated on two different rapid prototyping systems [7]:

- a six-DoF mobile manipulator for realistic full-body kinesthetic interaction, see Fig. 4(b).

The systems are driven by the modular software architecture ARCADE [8] with seamless interfaces to the open-source project ROS and real-time capabilities through MATLAB/Simulink’s Real-Time Workshop. The studies conducted to evaluate our research work proof our rapid prototyping systems’ capabilities in pHRI.

VI. CONCLUSION

This work presents an overview of our current lines of research in physical human-robot interaction (pHRI). In short, we cover the topics of learning, planning and control in presence of uncertain human actions. The contribution is to highlight the synergetic application of both learning and planning techniques, the disagreement-aware shaping of the robotic control input to the physical task, the development of role behavior to efficiently negotiate the physical effort, and our rapid prototyping environment enabling us to gain valuable insights and results of our schemes from pHRI-experiments.

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