PReWAP: Predictive Redirected Walking Using Artificial Potential Fields

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Abstract

In predictive redirected walking applications, planning the redirection and path prediction are crucial for a safe and effective redirection. Common predictive redirection algorithms require many simplifications and limitations concerning the real and the virtual environments to achieve a real-time performance. These limitations include for example that the tracking space needs to be convex, and only a single user is supported. In this paper, we present a novel approach called PReWAP which addresses many of these shortcomings. We introduce artificial potential fields to represent the real environment which are able to handle non-convex environments and multiple co-located users. Further, we show how this new approach can be integrated into a model predictive controller which will allow various redirection techniques and multiple gains to be applied.

Index Terms: Human-centered computing—Virtual reality; Computing methodologies—Motion path planning

1 Introduction

Since real walking in immersive virtual reality applications is limited by the size of the available physical space, Razzaque et al. [6] introduced Redirected Walking (RDW) to manipulate a user's perception of self motion. Using these manipulations, so-called redirection techniques (RETs), an extensive virtual environment (VE) can be explored in a small physical space while really walking, ideally, without the user noticing. These RETs are characterised by so-called gains (i.e. the strength of the manipulation), which are also used to quantify a threshold of perceptibility [7]. For choosing the most appropriate RET and its gain, there are two fundamental concepts: reactive and predictive redirection. Reactive redirection methods only select the next RET to be applied based on the current user state (i.e. position and heading), while long-term consequences of this selection are not considered (e.g. "Steer-to-Center" [5]). In contrast, predictive redirection algorithms predict potential walking trajectories and evaluate these potential future user states based on various conditions resulting in an optimal redirection, which efficiently prevents collisions with the real environment (RE) (e.g. FORCE [9], MPCRed [4]). These predictive algorithms rely on a tracking system observing the user's state and a model of the RE defining the walkable area and physical boundaries (i.e. the tracking space). So far, these tracking spaces needed to be static and convex in order to guarantee real-time planning and execution.

This paper introduces a concept that uses artificial potential fields (APFs) to represent the RE and thus addresses these limitations of current predictive RDW. Specifically, combining APFs with model predictive control will allow for non-convex, dynamic tracking spaces, which eventually opens the tracking space for multiple co-located users.

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2 Related Work

In general, RDW applications mostly require static tracking spaces which needed to be convex. Particularly for predictive RDW, these limitations were proved to be an effective measure to ensure a real-time execution [4,9]. Arbitrarily shaped tracking spaces and dynamic obstacles were only briefly discussed from a planning perspective using a singular virtual trajectory [2].

In these approaches, it was shown that reliable virtual trajectory prediction greatly improves the redirection. However, the prediction was simplified by using narrow virtual corridors arranged to a rectangular maze. In that way, virtual trajectory prediction is done using a bidirectional graph (i.e. edges connecting nodes which are placed at crossings or turns). The node closest to the user's position is chosen as a starting node and the predicted trajectory is aligned with the adjacent edge based on the user's heading.

Further, predictive RDW implementations to date are exclusively focused on a single user experience. The challenge of reactively steering multiple co-located users was addressed only on a conceptual level and with simulations of possible approaches [1]. However, there is currently no working method for combining predictive redirection methods with a co-located multi-user architecture.

3 Methodology

In this paper, we discuss the concept of "Predictive Redirected Walking using Artificial Potential Fields" (PReWAP) which relies on APFs to represent the RE's tracking space. We briefly describe a known simple path prediction and its integration into PReWAP. Then, we explain how APFs are built and how the path prediction and the APFs are processed in a model predictive controller. The complete process is split into three parts: Path prediction, APF representation, and the planning cycle.

3.1 Path Prediction

In order to predict virtual trajectories, we employ a path prediction similar to Nescher et al. [4]. The VE consists of a rectangular maze which is described by a skeleton graph as shown by Zank et al. [8]. Placing a node at each turn or crossing allows for a bidirectional link in between, which is used for the prediction. For each prediction, the user's current position is assigned to the closest node in the maze. Based on the smallest angular deviation between the heading and the adjacent edges, the predictive direction is found. Following this direction for a predefined number of nodes (i.e. the planning horizon N), the prediction generates a potential future trajectory.

3.2 APF Representation

The idea of representing a real space using APFs was first introduced by Krogh [3] for robotic path planning applications. However, in contrast to using APFs with robots and defined control inputs, applying it to humans instead poses new challenges. Real walking and specifically the user's spontaneous decision-making require the processing to be highly reactive to ensure a fast adjustment of the redirection to unexpected changes.

In navigational APFs, undesirable states (e.g. close to a wall or obstacles) are assigned a high potential which decreases with the distance from obstacles. Accordingly, states located outside the

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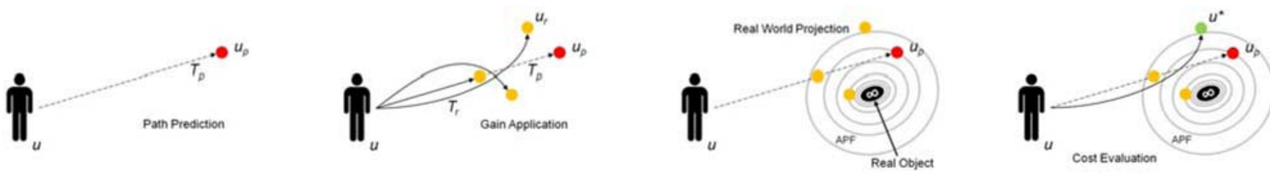

(a) The path prediction provides a predicted trajectory T_p which connects the current user state u to a predicted state u_p (red).

(b) Next, different RETs and various gains are applied to T_p. This results in a set of redirected trajectories T_r connecting u to redirected states u_r (yellow).

(c) The redirected states u_r and corresponding trajectories T_r are projected into the RE, specifically into the APF.

(d) The different states u_r are recursively evaluated based on the cost function, yielding an optimal redirection sequence RET^* connecting u to u^* (green).

Figure 1: The complete planning cycle of PReWAP: Prediction - Gain Application - Real World Projection - Cost Evaluation

walkable area or in real objects are initialised with an infinite potential to make them inaccessible. With this approach, arbitrary non-convex layouts can be easily represented since each geometry has a defined impact on the complete APF. Also, obstacles, both static and dynamic, and particularly other users can be integrated into this approach. In this case, the static environment (e.g. walls) forms a single static APF and dynamic obstacles or other co-located users generate their individual fields which are then added to the static field.

3.3 Planning Cycle

For this approach, we use a model predictive controller to recursively minimise a cost function over a given set of inputs (i.e. different RETs and various gains). This cost function combines the cost of the redirected user state u_r and the cost of different RETs and gains. Accordingly, the total cost for each u_r is determined from a linear combination of the corresponding APF value and a predefined look-up-table entry. This table is generated by classifying each RET and its gains by their noticeability. Consequently, more noticeable RETs (e.g. resets) or gains correspond to a higher cost. The recursive optimisation is evaluated over a fixed planning horizon N (i.e. the number of nodes).

A complete planning cycle for a single virtual trajectory is summarised in four steps:

1. Following the predefined graph and its nodes from the current user position u, the path prediction provides a predicted trajectory T_p. This T_p connects u to a predicted user state u_p (see Figure 1(a)).

2. Then, different RETs and various gains are applied to T_p yielding redirected trajectories T_r including their corresponding redirected states u_r (see Figure 1(b)).

3. The redirected trajectories T_r are projected into the real tracking space, represented by the APF (see Figure 1(c)). Now, invalid u_r can immediately be discarded due to the infinite potential in unreachable real areas since these do not need to be taken into consideration in the recursive evaluation.

4. The cost function is recursively evaluated over all T_r which results in an optimal sequence of redirection RET^* (see Figure 1(d)).

Minimising the cost function over N results in an optimal redirection sequence $RET^*(= [RET_0^*, RET_1^* ..., RET_{N-1}^*])$ for the user state u. In order for the controller to be adaptive to spontaneous user behaviour, only RET_0^* is applied before a new planning cycle is initiated.

4 Conclusion and Future Work

In this paper, we showed the conceptual approach for PReWAP, which uses APFs to represent the RE in predictive RDW. Combining the cost of the redirection and the user's predicted state in the APF, an optimal RET and gain are identified. Concluding, PReWAP removes the constraints of a static convex RE and allows for arbitrarily shaped tracking spaces containing dynamic obstacles. Notably, this will also enable multiple co-located users at the same time.

Future work will focus on a step-wise implementation of PReWAP. Then, in order to evaluate PReWAP's efficiency against other solutions, e.g. MPCRed, a similar geometry, and as a comparative measure, the number of occurring resets and mean redirection will be used. In a subsequent step, mobile targets will be integrated and various collision avoidance algorithms will be tested. Further, to address the limitations of the current VE to corridors, caused by the node-based prediction, we aim to implement a novel short-term path prediction which will make this virtual corridor constraint obsolete. Accordingly, this approach will extend PReWAP to be able to handle virtual open spaces.

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