A Path Smoothing Strategy Based on Harmony Search Algorithm for Probabilistic Foam

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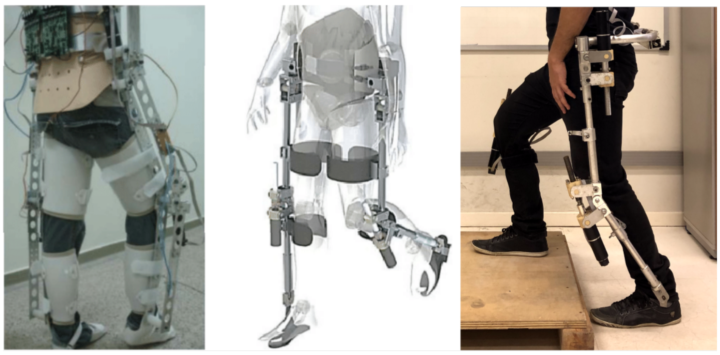
Abstract. *Probabilistic Foam method (PFM) is an attractive path planner, ideal for applications in assistive robotics which demands safety. However, its planned paths are not smooth. Then, path smoothing strategies need to be applied for PFM to improve the paths. This paper presents an optimization approach based on Harmony Search algorithm to smooth PFM paths. Simulated experiments using an exoskeleton to overcome an obstacle were performed to test our methodology. Results show that our approach is capable of smoothing paths for the exoskeleton, which results in more anthropomorphic motions.*

1. Introduction

Path planning is one of the most important issue on robotics, since it calculates a set of configurations that a robot must perform to move from a point to another one, without colliding with obstacles [Latombe 1991]. The sampling-based path planning are the most promising planners since they can find feasible paths by sampling random free configurations using few computer resources, such as Probabilistic Roadmaps (PRM) [Kavraki et al. 1996] and Rapidly-Exploring Random Tree (RRT) [Lavalle 1998].

The assistive robots are devices that perform actions that benefit people with some disabilities. For example, the project Ortholeg is a lower limb exoskeleton that helps physically challenged people in assisted walking. Ortholeg was designed with the concept of transparency, which can be defined as the capability of the device to make the walking experience as natural as possible, both for the user and the people around him [Melo et al. 2017]. Figure 1 illustrates the exoskeleton used in this study.



(a) (b) (c)

Figure 1. Project Ortholeg. (a) Version 1.0. (b) and (c) Version 2.0 in development.

In [Nascimento et al. 2018], a planner called Probabilistic Foam was applied to provide safe movements for the exoskeleton to overcoming a single obstacle. Probabilistic Foam method (PFM) [Silveira and Alsina 2016] guarantees a free-obstacle path with high clearance for safe maneuverability. A problem with the approach presented in [Nascimento et al. 2018] is that the paths generated are non-smooth, which implies that the motion performed was non anthropomorphic.

Optimization techniques are indicated for path smoothing problem with many constraints. Among the optimization methods, the Harmony Search Algorithm (HS) [Geem et al. 2001] is a metaheuristic with some interesting features and better results in comparison with other algorithms [Piarehzadeh et al. 2012, Kim et al. 2019]. In this way, this work presents the application of HS algorithm to optimize the path obtained by PFM, generating smoother paths. We used as study case the planning the task of overcoming a simple obstacle by the exoskeleton Ortholeg.

2. Harmony Search Algorithm

Harmony Search (HS) is a metaheuristic inspired in musical concepts [Geem et al. 2001] where finding the perfect harmony in music is analogous to finding the optimality in optimization. Figure 5 shows this analogy, where the musical instruments are the decision variables and the notes are the range of each variable. The harmonies represent the candidate solution of the problem and the people reaction is the objective function.

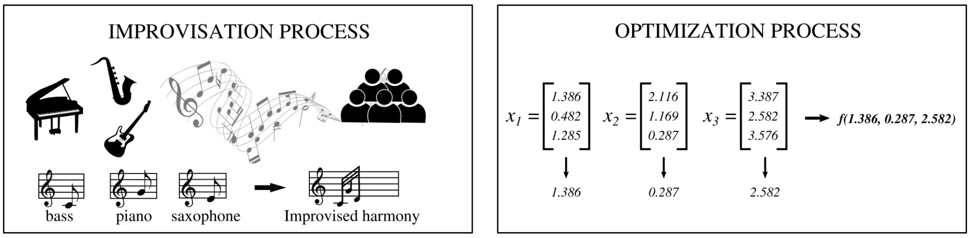


Figure 2. Musical improvisation process versus optimization process.

The steps of HS algorithm are: Initialization of the HS parameters and Harmony Memory (HM), Improvisation of a new harmony, HM Update and Stopping criteria verification. The HS parameters are: Harmony Memory Size (HMS), Harmony Memory Consideration Rate (HMCR), Pitch Adjustment Rate (PAR), BandWidth (BW). The HM is a vector that contains HMS harmonies. The parameter HMCR indicates the probability of selecting an existing harmony from HM during the improvisation process and finally, PAR and BW are parameters related to adjustments in the harmony.

The initialization of the HM is by sampling HMS random vectors. During the improvisation process, a harmony h is selected from HM with probability HMCR. The adjustment of the harmony h generates a new harmony h_{new}:

$$h_{new} = h \pm x \times BW, \quad x \in U\left([0,1]\right) \tag{1}$$

where x is a random value uniformly distributed on [0, 1], and BW is a parameter between [0,1] that provides the adjustment.

The new harmony is evaluated using the objective function. If h_{new} is better evaluated than the worst harmony inside HM, the h_{new} replaces this worst harmony. Finally, while the stopping criteria is not achieved, new harmonies are improvised.

3. Probabilistic Foam Method

Probabilistic Foam method (PFM) [Silveira and Alsina 2016] is a path planner with the main feature of generating paths for safe maneuverability. In [Nascimento et al. 2018] it was proposed an implementation of PFM, such that, the basic structure of PFM, the bubble, was computed in the configuration space $\mathcal{C}$ using distance information from workspace $\mathcal{W}$, based on the concept of *bubbles of free space* [Quinlan 1995].

A bubble b with radius r, centered in q is defined as a volumetric hyperspherical. The planning of overcoming an obstacle considers the configuration vector $q = [\theta_{\text{h}}, \theta_{\text{k}}, \theta_{\text{q}}]^T$, which denotes the hip joint, the knee joint and the displacement of the hip, respectively. In this way, the bubble is defined as a 3-*ball* and its surface is a 2-*sphere* in $\mathcal{C}$, as can be seen in Fig. 3b. The path planning will return a path from the initial configuration q_{init} to the goal configuration q_{goal}, providing the motion shown in Fig. 3a.

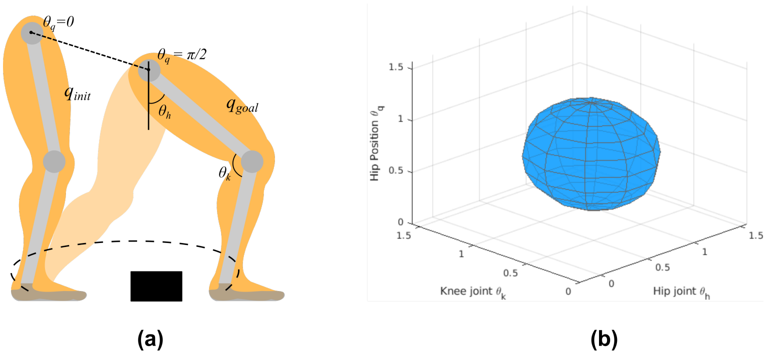


Figure 3. (a) Leg positions in $\mathcal{W}$. (b) Illustration of a bubble in $\mathcal{C}$.

3.1. Foam Propagation

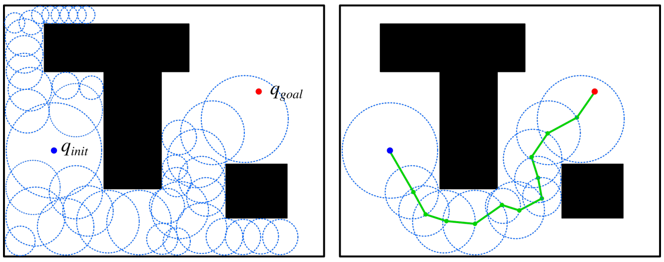
The probabilistic foam F is a structure defined as a set of bubbles, $F = \cup b$, constructed incrementally from the b_{init} (i.e., bubble centered in q_{init}) to b_{goal} (i.e., bubble that encircles q_{goal}) in the free space. This propagation occurs by expanding children bubbles on the surface of parent bubbles from the previous generation. The maximum number N of children bubbles for each parent bubble is defined by:

$$N = K\left(\lfloor r/r_{\text{min}} \rfloor\right)^{n-1} \tag{2}$$

where n is the dimension of $\mathcal{C}$, r is the radius of the parent bubble and r_{min} is the radius of the smallest allowed bubble. K is a constant value related to the maximum number of children bubbles for the parent bubble with radius r_{min}.

N random configurations are sampled on the surface of the parent bubble. Bubbles sampled in regions covered by other bubbles are removed. Besides, a child bubble can be expanded only if its radius is $r \geqslant r_{min}$. The foam propagates until a child bubble encircles q_{goal}. Figure 4a shows the probabilistic foam for a space $n = 2$. When the algorithm finishes, a structure called Rosary can be found, as shown in Figure 4b.

The Rosary $\mathcal{R}$ is a sequence of k overlapped bubbles, from goal bubble b_{goal} to initial bubble b_{init}. A feasible path can be extracted from the rosary by linking line segments through the center of the bubbles, as can be seen in Fig. 4b (green line). If the path crosses the intersection region between all consecutive bubbles, the path is safe. In this way, path smoothing strategies need to improve the path maintaining these safety constraints.



(a) (b)

Figure 4. (a) Probabilistic foam. (b) Extracted rosary and found path.

4. Path Smoothing as an Optimization Process

In order to model the path smoothing as an optimization problem, we need to deal with two main issues: The decision variables (harmony vector for HS) and the objective function. Consider the rosary and path shown in Figure 5.

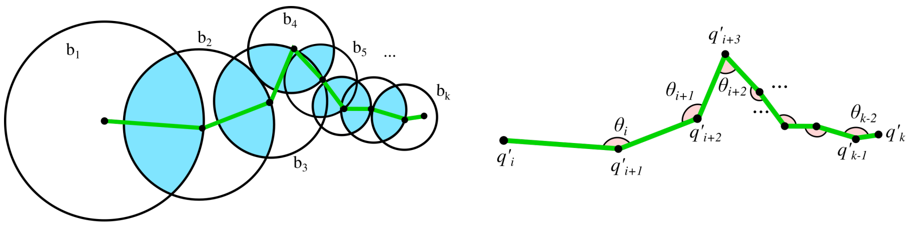


Figure 5. Illustration of a path extracted from the rosary.

The blue region is the intersection region between two consecutive bubbles b_i and b_{i+1}, which represents the path constraints. In the optimization process, the points q' of the path σ must to be bounded by the blue region. The harmony vector (path) is $\sigma = \{q'_1,\ q'_2,\ ...,\ q'_{k-2},\ q'_{k-1}\}$, where k is the number of bubbles in the rosary.

4.1. Objective Function

In order to evaluate each path, we used the angles θ_i between line segments, as shown in Figure 5. We consider that the pair of line segments are smoothest when the angle value is $\theta_i = \pi$. Besides, for the special case of the exoskeleton, we also consider that it is important to decrease the path length σ_{length}. The objective function for this problem is:

$$\min f(\sigma) = \frac{\sum_{i=1}^{k-2}(\pi - \theta_i)}{k-2} + \sigma_{length}, \quad \text{such that:} \quad q'_i \in (b_i \cap b_{i+1}) \tag{3}$$

where $b_i \cap b_{i+1}$ is the *hatch* region between two consecutive bubbles. The minimization of the function $f(\sigma)$ indicates that the angles θ_i are getting closer to π, resulting in smoother paths. Moreover, using the σ_{length} information, the paths also become shorter.

5. Results

In order to perform the path planning using the Probabilistic Foam method for the scenario where the exoskeleton must overcome a simple obstacle (Figure 3a), we used the parameters $K = 10$ and $r_{min} = 0.07$. The initial configuration was $q_{init} = [0.2\ 0.3\ 0.08]$ rad, and the goal configuration was $q_{goal} = [0.45\ 0.4536\ 1.45]$ rad. The simulation results of path planning with PFM are shown in Figure 6.

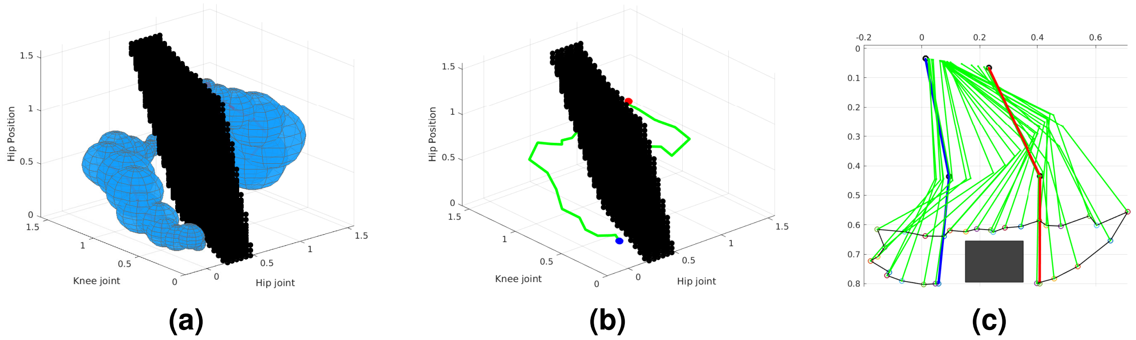


Figure 6. Path planning for the exoskeleton using PFM. (a) The rosary found. (b) Path extracted from rosary. (c) Motion performed for the planed path.

The PFM generated a probabilistic foam where it was possible to obtain a rosary, as can be seen in Figure 6a. A path could be extracted from this rosary through linking the center of each bubble by line segments, as shown in Figure 6b. This generated path is non-smooth, which resulted in a non anthropomorphic motion, as illustrated in Figure 6c.

Using the optimization technique HS, it was possible to improve the path, as can be seen in Figure 7. The HS parameters were $HMCR = 0.99$, $HMS = 50$, $PAR = 0.15$, $BW = 0.01$ and $NI = 2 \times 10^4$. These values were obtained by experiments.

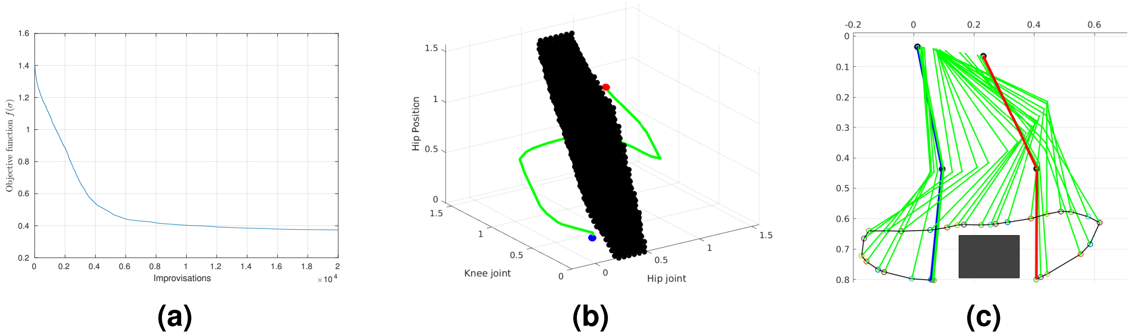


Figure 7. Path smoothing result using HS. (a) Convergence curve for the optimization. (b) Smoothed path by HS. (c) Performing of the improved motion.

The graph shown in Figure 7a indicates the average of the function f for all harmonies in HM. The path related to the best harmony improvised can be seen in Figure 7b. Using the objective function it is possible to see how much the function was minimized, where the original path was $f(\sigma) = 0.9584$ and the smoothed path was $f(\sigma) = 0.3736$. Besides, it is possible to observe that the smoothed path provided a more anthropomorphic motion, as illustrated in Figure 7c.

The selected parameters provided a satisfactory optimization of the path. However, this process was slow, since that 2×10^4 improvisations were necessary to improve the path. The function decreases faster in the first 8000 improvisations and after it, the function does not change so much as the improvisations get higher, as seen in Figure 7a.

6. Conclusion

This work presented a strategy to smooth paths obtained by PFM, based on Harmony Search Algorithm. The methodology presented some satisfactory results providing a more anthropomorphic motion for the exoskeleton. Besides, the smoothed path kept bounded by the bubbles from rosary, which means that the path remained safe.

A drawback of the method for the studied scenario is that it was necessary a high number of improvisations to provide acceptable results. However, it was implemented a basic HS and perhaps improved HS variants can deal with this issue. In this way, in future works we intend to find strategies to improve the convergence process for harmony search. Finally, we also intent to study about the computational effort for this approach.

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