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Rethinking Shortest Path: An Energy Expenditure Approach

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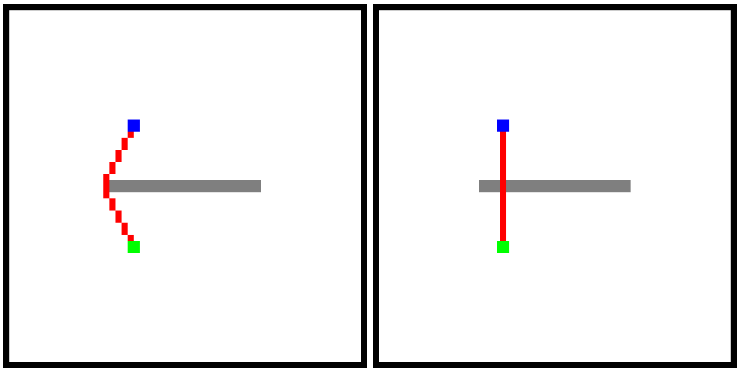

Figure 1: *The presented approach computes the path that minimises the energy expenditure of the character (left panel) rather than the path with the shortest length (right panel). In both panels, the grey area denotes a single stair, the green dot is the starting position, the blue dot is the goal position, and the red line is the executed path.*

Abstract

Considering that humans acting in constrained environments do not always plan according to shortest path criteria; rather, they conceptually measure the path which minimises the amount of expended energy. Hence, virtual characters should be able to execute their paths according to planning methods based not on path length but on the minimisation of actual expended energy. Thus, in this paper, we introduce a simple method that uses a formula for computing vanadium dioxide (VO_2) levels, which is a proxy for the energy expended by humans during various activities.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Animation I.2.11 [Artificial Intelligence]: Distributed Artificial Intelligence—Intelligent Agents

1. Introduction

Using vanadium dioxide (VO_2) parameter, this paper introduces an energy minimisation approach for the path execution and planning process. Specifically, energy requirements can be expressed in terms of the oxygen requirements of a given physical activity. Levels of VO_2 provide useful information for measuring the energy costs of physical activities, generally expressed in units of kilocalories (*kcal*). By measuring VO_2 levels, it is possible to predict the energy expenditure in a specified task. To examine the energy expenditure of a virtual character, we use a mathematical equation that returns an approximation of the VO_2 expenditure for different actions, as a parameter to describe the expended

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energy of a character performing a given task. Hence, besides the measurement of the shortest path distance, which is based on length units (e.g., centimetre, meter, kilometre etc.), we propose that the VO_2 required for each step (in units of $ml * kg^{-1} * min^{-1}$) should be also considered.

Thus, we present a method in which the character's path is not the path that minimises the distance, but the path that minimises the amount of expended energy. Figure 1 illustrates the two approaches, in which the path is based on geometrical measurements that minimise the path length (right panel), and a second path that minimises the amount of expended energy (left panel). The presented method can be especially beneficial in cases where, during path planning, two or more paths have the same length. Hence, the quantitative value returned by the VO_2 parameter can be used as an additional measurement (or heuristic) for a planning algorithm. Moreover, the presented approach employs the ability to execute a path based on different types of steps, where each step represents either walking or stair stepping activities. Thus, the final path will be the path for which the sum of the individual steps minimises the amount of expended energy.

The remainder of the paper is organised as follows. In Section 2, we present work related to path planning techniques. Section 3 presents the human factors that should be considered in path planning processes. Section 4 examines the proposed methodology in conjunction with the path execution process. Finally, in Section 5 we conclude by discussing the advantages of the proposed solution.

2. Related Work

One of the most well-known approaches for executing the shortest path problem uses search-based algorithms such as A^*, introduced by Hart et al. [HNR68] in 1968; these algorithms are responsible for returning the shortest path, if one exists. The techniques have been thoroughly examined in cases of path planning, especially by the games development community, which uses low-resolution grid solutions. On the other hand, flexible path planning techniques, such as the Potential Field [Kha86] [KV88] method, were introduced approximately 20 years ago. In the potential field method, the character is driven through an artificial potential field, which is defined by a free configuration space; one of the advantages of this method is its ability to execute smooth paths. However, the computation of such algorithms is relatively expensive, and the methods cannot be executed in real time. On the other hand, a dynamic perspective of potential fields introduced by Treuille et al. [TCP06] in a crowd simulations system. In this case a set of dynamic potential and velocity fields generated over the domain that guide all individual agents.

Techniques based on Roadmap methods, such as Visibility graphs [Lat90], Rapidly-exploring Random Trees [KL00], and the Probabilistic Roadmap Method [KSLO96] [AW96] [BKL*97], while not examining local minima, ensure the return of a path, if one exists. In addition, in recent years, techniques have been proposed that use Voronoi diagrams [HCK*99] [Roh91] to plan and execute paths. Recently, techniques such as the Corridor Map Method [GO07] [KO04] have been determined as beneficial for high quality path planning, as they combine the ability to direct global motions using high-quality roadmaps and to have local motions controlled by potential fields, thus providing local flexibility of the path.

From a review of the literature, we found only two approaches that mention the computation of expended energy in the completion of a given task by a virtual character. The first approach, proposed by Levine et al. [LLKP11], refers to a space-time action locomotion controller. However, Levine et al.'s approach is based on a cost function that assigns a lower cost per second to the waiting controller that is assigned to the character. Hence, to the best of our knowledge, energy minimisation approaches like the one presented in this paper, have not yet been examined and implemented in path planning algorithms. The second approach, computes the energy required by a character during the path planning process [GCC*10]. This methodology tries to minimise the biomechanical energy of a character by assigning the corresponding path. Despite the similarity with the approach presented in this paper, the main difference is that the presented approach tries to simulate the ability of a character that chooses either to avoid or not a single stair (denotes as obstacle) in the three-dimensional space. This is achieved by measuring the energy that a character requires for each single step, which is something that is not provided in [GCC*10], where only the walking locomotion of the character is measured.

3. Human Factors

The normal walking velocity of humans (v_{human}) has been estimated as $1.2m/s$ based on the U.S. Manual of Uniform Traffic Control Devices (MUTCD) [FHA03], and $1.1m/s$ to $1.4m/s$ based on Manual of Uniform Traffic Control Devices for Canada (MUTCDC) [Tra02]. The approach in this paper requires the computation of the length of each single step of the character, as the human energy output per step depends on the step length. Previously, step length s_{length} has been empirically determined, based on the measurements of Grieve [Gri68], to obey a power law $s_{length} \approx v_{human}^{\beta}$, where the value of β in adults is approximately $\beta = 0.42$. In our calculations, the value of s_{length} is determined from estimations of character velocity; the number of steps can then be determined from the step length and the distance from the start to the goal position.

The presented approach should also be able to compute a path, which minimises the energy expenditure of the character, based on the goals and actions required, including stair stepping actions as well. The factors that influence the latter actions must also be defined. Firstly, based on Warren's empirical measurements of leg segments [War84], a critical stair height p_{max}, (i.e. the stair height which is impossible to climb bipedally), is defined such as $p_{max} = 0.88m$. Thus, the critical p_{max} value that describes "climbability" can be used as an upper limit of the height of a generated stair. However, while the stair height is required to solve the approximate energy use based on VO_2, the measurements of Warren Jr [War95] show that the optimal point p_0 that denotes the stair height which minimises the energy expenditure during stair stepping, should be $p_0 = 0.26m$. In addition, Templer [Tem75] determines that the optimal stair stepping frequency s_f for stairs with a height $s_h = 10in$ ($\sim 0.25m$), is approximately $50steps/min$.

4. The Proposed Method

The computation of the expended energy during a given task must be considered in terms of the individual components of the process. A path can be represented by a finite number of steps. This is quite important, especially in cases where the computation of the energy during walking, or walking over the stairs, is desired. Thus, our research considers the motions in terms of VO_2 consumption, which adequately describes possible actions in a quantitative manner. The energy expenditure based on VO_2, as introduced by the American College of Sports Medicine (ACSM) [GD07], is computed from Equation 1 as:

$$VO_2 = H + V + R \quad (1)$$

where H and V denote the horizontal and vertical components of the activity, respectively, and R denotes the resting component (which is constant, $R = 3.5$).

4.1. Walking Step Energy Expenditure

When humans, or in this case virtual characters, are called upon to perform walking motions, Equation 1 becomes:

$$VO_2 = 0.1 * v_{walk} + 1.8 * v_{walk} * h_{fg} + 3.5 \quad (2)$$

where v_{walk} denotes the velocity of the human during walking and h_{fg} is a fractional grade, which may be assigned a value of $h_{fg} = 0.13$, based on the protocol of Bruce [BPLJ*49]. In the presented approach, the computation of the energy expenditure is based on single steps; thus, the solution depends on optimisation of Equation 1.

The optimisation of Equation 1 requires the following assumptions. Based on MUTCDC [Tra02], v_{human} is assigned a value of $1.1m/s$. Substitution of v_{human} into the equation of Grieve [Gri68] ($s_{length} \approx v^{\beta}_{human}$) gives $s_{length} \approx 1.05m$. These values allow the calculation of $v_{walk} = 1/0.95$ $(step/sec)$. Additionally, since R is a constant value, it is not taken into account.

Based on these assumptions, the VO_2 for each simple walking step of the character is first computed. This calculation is important in the presented approach, as the shortest path execution process is divided into single steps in which the amount of energy expended in the execution of the locomotion actions is minimised.

4.2. Stair Step Energy Expenditure

As mentioned above, the advantage of computing VO_2 is that researchers can approximate the computation of various actions based on Equation 1, as well as on data in the ACSM [GD07]. Hence, the approximate energy expended by a human during stair stepping is described by:

$$VO_2 = 0.2 * s_f + s_{comp} * 1.8 * s_h * s_f + 3.5 \quad (3)$$

where s_f is the step frequency (min^{-1}), s_{comp} is the stepping component, described by Equation 4 and s_h is the stair height in meters.

$$s_{comp} = \begin{cases} 1 & \text{if } stepping\ up \\ 0.33 & \text{if } stepping\ down \end{cases} \quad (4)$$

As previously described, for the computation of walking energy the stair stepping formula should be optimised to separately compute the expended energy at every step. In this case, based on Templer [Tem75], the stair step frequency for stairs with height $s_{h(0.25)} = 10in$ ($\sim 0.25m$) is approximately $s_{f(0.25)} = 50steps/min$. However, while the step frequency is related to the step height, the step frequency $s_{f(i)}$ for a given stair with height $s_{h(i)}$ is computed as $s_{f(i)} = s_{h(i)} * s_{f(0.25)}/s_{h(0.25)}$. Hence, Equation 3 becomes:

$$VO_2 = 0.2 + s_{comp} * 1.8 * s_h * s_{f(i)} + 3.5 \quad (5)$$

The result of computing VO_2 for both walking and stair stepping, allow us to approximately calculate the expended energy in a quantitative way. Hence, even if empirical values are used for solving the energy expenditure for a single-task problem, Equation 5 closely approximates an actual human decision that takes into account different action tasks. In addition, it should be mentioned that approximate values are used in planning tasks that solve the shortest path problem, rather than incorporating human motion data directly, which may extend each single parameter of the previously mentioned formulas.

4.3. Minimum Energy Expenditure Path Execution

To determine the minimum energy path, the approach first computes every possible path from the starting position P_S to the goal position P_G. The desired path Π can be characterised by executed states of the form $\Pi_{S \to G} = \{\pi_1, ..., \pi_n\}$, where n denotes the number of steps required to achieve the goal position P_G. In this case, Dijkstra's algorithm to compute the shortest path, which is based on the possible states of the

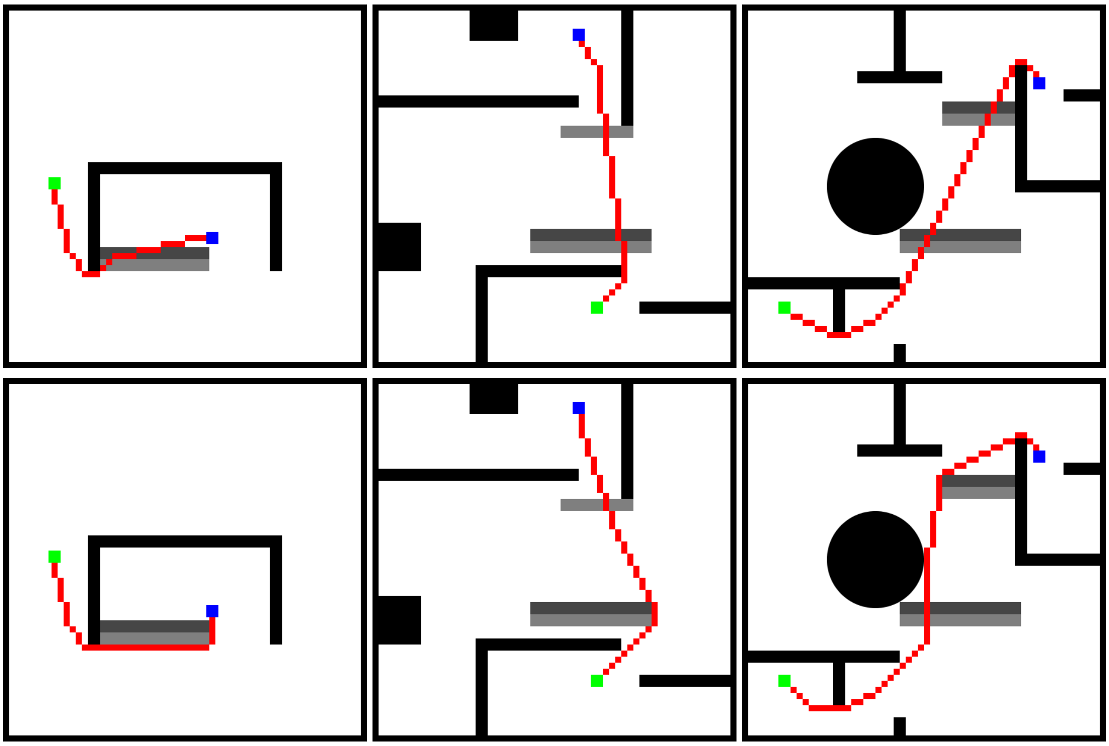

Figure 2: *Example paths, between the start (green) and goal (blue) positions generated using Dijkstra's algorithm to measure the path with the minimum length (upper row) and the path with the minimum expended energy (lower row). The stair height is* $s_h = 0.25m$ *for the light grey stairs and* $s_h = 0.55m$ *for the dark grey stairs. The difference between the heights of the two stair types is the height of the second step in a two-stair sequence.*

environment as well as the length of the path, results in the sum of the lengths of each simple step s_{length}; however, this approach returns a path for which the expended energy has not been computed.

Hence, implementation of Dijkstra's algorithm requires calculations of the energy expenditure of the character in moving from the current position to all possible candidate step positions. Thus, for each target state, an approximation of the VO_2 required to achieve the goal must be added to the algorithm. Then, rather than computing the minimum distance between π_i and π_{i+1}, which returns the shortest path length $L(\Pi_{S\rightarrow G})$, where $L(\Pi_{S\rightarrow G})$ is computed for all possible sampling states π, the approach computes the path $E(\Pi_{S\rightarrow G})$ which minimises the energy expenditure E required to move from the π_i to π_{i+1} state. Considering that for any given state, the energy requirement of the character e_Π can be computed from VO_2, as previously presented for both stair stepping and simple stepping actions, the path extraction process should satisfy Equation 6:

$$E(\Pi_{S\rightarrow G}) = min \sum_{i=1}^{n} e_i \quad (6)$$

With this simple approach, it is possible to compute an optimal path for the character minimising the total amount of energy. Some example paths computed using Dijkstra's algorithm, based on both the shortest length and the minimum energy expenditure, are illustrated in Figure 2.

4.4. Application

The proposed method was implemented in an interactive application. Hence, a simple locomotion controller similar to the one proposed by Treuille et al. [TLP07] along with the path following technique proposed in this paper, gives the ability to produce the desired locomotion of the virtual character that follows the executed path. An example of the path following method is illustrated in Figure 3.

5. Conclusions

This study introduces an energy parameter that can influence the calculation process of a character's shortest path. Our assumption in adding this parameter is that humans in their everyday life do not only consider solutions that minimise the distance to reach target positions, but also consider

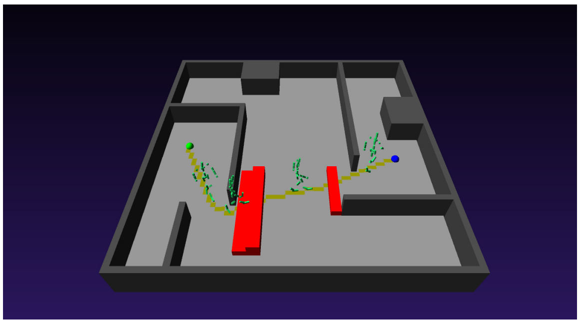

Figure 3: *A character following the executed path, based on the implementation of a locomotion controller in conjunction with the proposed path execution method.*

solutions that minimise their energy expenditure. Thus, by implementing a path planning approach based on empirical formulas for VO_2 levels, which are related to the energy expended by actual humans in real life, it is shown that the shortest distance is not always the path that minimises energy expenditure. The paper also indicates that future path planning methods could implement a variety of approaches in which not only the energy but also other physical characteristics of human characters could be modelled, such as the stamina of a character. Finally, in a future implementation we will try to examine the ability of integrating the energy constraints to dynamic environments by integrating physical human measurements such as [MNA13]. Thus, we assume that a high quality humanlike space-time motion planning model could be generated.

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