Full-body Animation of Human Locomotion in Reduced Gravity using Physics-based Control

Yun-hyeong Kim[1], Taesoo Kwon[2], Daeun Song[1], and Young J. Kim[1]

[1] *Department of Computer Science and Engineering, Ewha Womans University, Republic of Korea*

[2] *Department of Computer Science and Engineering, Hanyang University, Republic of Korea*

yhyh1202@ewhain.net, taesoo@hanyang.ac.kr, daeun7250@ewhain.net, kimy@ewha.ac.kr

Abstract—We propose a new physics-based approach to simulate the full-body animation of human locomotion in a reduced gravity environment, such as the Moon or Mars. As input, our method takes motion-captured human motions under Earth's gravitational condition and builds an inverted-pendulum on cart (IPC) control model, which is analyzed using the motion-captured data. Then, for a given gravity condition, we first estimate the desired velocity as well as stride frequency of our character model using the *Froude number*, map its control model to the altered gravity and plan footsteps that can match the given environmental condition. Using our technique, we can generate stable and robust human gaits in reduced gravity including different gait characteristics. We also compare our results to a known, analytical gait model in the biomechanical literature for reduced gravity, and verify that our method matches the results.

Index Terms—I Computing Methodologies, I.3 Computer Graphics, I.3.5 Computational Geometry and Object Modeling, I.3.5.i Physically based modeling, I.3.7 Three-dimensional Graphics and Realism, I.3.7.a Animation

1 Introduction

MANNED space exploration is all humanity's dream. Such thought can be traced back to the early history of mankind. The dream finally came true in 1969 by the Apollo mission. One of the critical components to making this mission possible was to understand how human's motion can be affected and thereby adapt to the reduced gravitational environment such as the Moon. This is a challenging problem, as it is necessary to generate anti-gravitational pull and apply it to a live human subject. Thus, prominent space programs such as NASA or ROSCOSMOS and biomechanical gait researchers made various attempts for altered gravity simulation using supine and erect cable suspension, parabolic aircraft flights, water immersion, and centrifugal methods. Even though these physical approaches are effective and indispensable for astronauts, they can be dangerous at times, costly to build, or difficult to reproduce the results and collect their data to analyze them afterward.

On the other hand, computer-based simulation techniques also have been employed to study human motions under reduced gravity conditions. These techniques are largely inspired by biomechanical research, and are based on a simplified human model in low dimension. Even though these attempts are useful in that they match the results of the physical experiments to some degree, they are still limited in terms of generating a diverse set of human gaits in a realistic setting. Moreover, lack of full-body simulation makes the results less visually appealing and is a serious limitation to be used for computer-graphic or computer-animation applications such as movie VFX, video games or virtual reality.

The ability to simulate full-body characters in computer has a wide range of potential uses in graphical and biomechanical applications, because simulated characters can adapt to changes in the environment such as gravity. Many physics-based character controllers have been presented that produce robust motion for locomotive behaviors including walking and running on flat, sloped and uneven terrains. However, most earlier control techniques assume that the simulated character moves in Earth's gravity. Direct application of these techniques to a reduced-gravity environment would not work due to the following reasons. The underlying control model is designed for human locomotion in Earth's gravity. Moreover, existing bipedal control techniques assume a certain pattern of footstep sequences which will determine the motion of the rest of body; however, such a pattern should be modified in a different gravity environment from that of Earth [1].

Main Results In this paper, we propose a new physics-based approach to simulate the full-body animation of human locomotion in a reduced-gravity environment, such as the Moon or Mars. As input, our method takes motion-captured human motions under Earth gravitational condition (i.e. $1g$), including walking, running, and turning, and builds an inverted pendulum on a cart (IPC) control model, which is analyzed and combined with the center of mass (COM) trajectories of the motion-captured characters. Then, for a given gravity condition, such as $\frac{g}{3}$ for Mars or $\frac{g}{6}$ for the Moon, we map the control model to the altered gravity and plan footsteps that can match the reduced-gravity dynamics of the pendulum. Using our technique, we can generate stable and robust human gaits in reduced gravity including different gait characteristics. We also compare these results to an analytical model using the well-known *Froude number*, and verify that our method matches the results known in the biomechanical literature on reduced gravity. To the best of our knowledge, our work is the first work that can simulate the full-body simulation of a human bipedal character in reduced gravity in high dimension with a diverse set of gait styles. A video accompanying this paper submission can be watched via the following link https://youtu.be/y14cNQvWVyQ.

2 Previous Work

In this section, we survey prior works relevant to bipedal locomotion under reduced-gravity conditions and physics-based character control.

2.1 Bipedal Locomotion and Simulation in Reduced Gravity

It is known in gait biomechanics and neurophysiology that gravity has a strong impact on terrestrial bipedal locomotion including limb oscillation rates, optimal walking speed, muscle activity patterns and gait transition speed, and thus extensive research has been conducted in these areas in the past. The purposes of these research works focus on gait rehabilitation, understanding the physiological effects of gravity, and astronaut training.

The *dynamic similarity* based on the *Froude number* F_r is the most important and common concept employed by the earlier research to understand bipedal locomotion in reduced gravity. The dynamic similarity implies that despite differences in body size, humans change from walk to run close at $F_r = 0.5$ and the optimal walking speed corresponds to $F_r = 0.25$ [2]. More importantly, the Froude number still remains the same for the transition and optimal walking speed regardless of a level of gravity, which provides a useful tool to estimate walking/running speeds for a given character model under different gravity conditions.

Most of existing, practical bipedal simulation in reduced gravity relies on a physical setup such as vertical or tilted body support system. Thus, in general, it is difficult to tune the system to a different gravitational environment, not to mention that it is also costly to build a robust system. On the other hand, there are a few exceptions of computer-based simulation for bipedal simulation in reduced gravity. Ackermann and Bogert studied predictive simulation of gait at a low gravity and showed that skipping is the preferred locomotion strategy [1]. Their simulation is based on a musculoskeletal model combined with a penalty-based contact model. But the simulation was conducted only for a lower body in two dimensions.

2.2 Physics-based Character Control

Physics-based locomotion control has been an important problem in the field of computer graphics because of its potential to adapt to unexpected perturbations. Early controllers often used hand-designed finite state machines and feedback rules for balance control. Others have used the preview control of simplified dynamic models abstracting the human body for an efficient low-dimensional planning [3], [4], [5].

Recently, per-frame optimization has been used for designing controllers that have improved stability and robustness. Instantaneous control signals are often obtained by formulating a QP (Quadratic Programming) problem, which can be solved efficiently in an online manner [6], [7]. These approaches compute joint torques and contact forces by minimizing objective functions while satisfying the law of physics. da Silva and colleagues produced a control system that combines quadratic programming with a preview control of a three-link pendulum [6]. Muico and colleagues simulated high-quality and agile movements such as sharp turns [8]. de Lasa and colleagues introduced a controller based on high-level features such as a center of mass and angular momentum [7]. Mordatch and colleagues improved the robustness of the controller using a spring-loaded inverted pendulum (SLIP) model [4].

Existing control algorithms can be further improved using controller optimization techniques. Some researchers optimized the parameters of a baseline controller to improve motion quality and robustness to unexpected disturbances or changes of terrains. Others optimized reference trajectories to solve locomotion control problems. Often, reference tracking controllers used motion capture data because of its advantage for reproducing believable human motion [5], [9]. Such data-driven approaches have demonstrated that subtle details and nuances in original human motions can be reproduced. However, the issue of how to generalize an existing motion to a highly different situation, for instance in different gravity than $1g$, has not been fully explored.

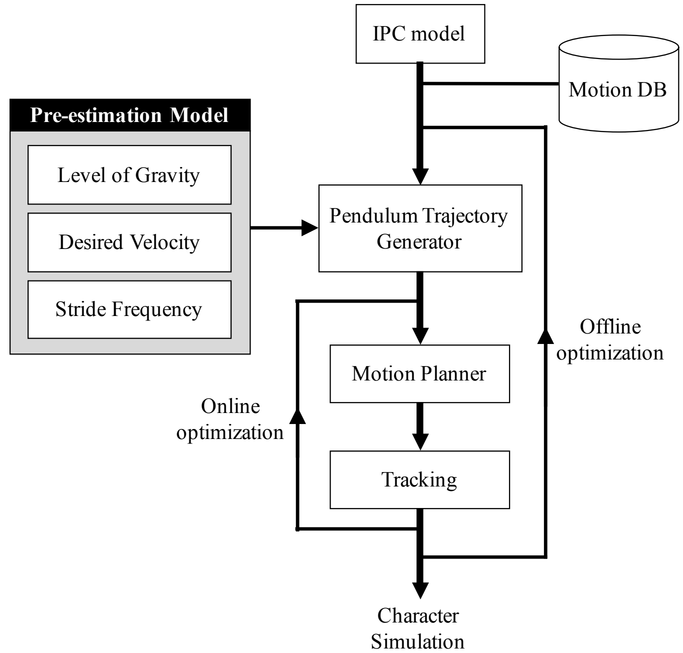


Fig. 1. System diagram

3 Overview of Our Approach

Our bipedal simulation is based on an IPC model, that estimates the current state of motion, predicts a short future horizon of the next motion, and maintains the balance of a character. As shown in Fig. 1, our approach consists of four main steps: pre-estimation model, pendulum trajectory generator, motion planner, and tracking.

Our system takes a level of gravity as well as a set of motion data captured in Earth's gravity including walking, running and turning. Each motion type is annotated with a state machine; for instance, the walking and turning motions have four states and the running motion has two states.

The pre-estimation model predicts the desired center-of-mass (COM) velocity and stride frequency of the target character in reduced gravity using the *Froude number*. From the predictive motion, we test if the motion is stable and looks natural. If so, we gradually increase the forward COM velocity and modify the stride frequency accordingly as long as the character moves stably.

At every simulation timestep, the pendulum trajectory generator first estimates the state of the IPC model by aligning a captured pose to the current pose of the simulated astronaut. Then, a short future horizon of the pendulum trajectory is planned based on the current estimate of the pendulum state and using the desired velocity determined by our pre-estimation model. Then, the motion planner converts the pendulum trajectory into a desired trajectory of the character motion that includes footstep locations using an inverse kinematics solver. The dynamic motion is synthesized by tracking the desired motion in an online manner. Finally, we generate full-body motion adapted to the surrounding environment. To reproduce a more stable and natural motion, an offline optimization process is executed to find optimal end-effector positions.

4 Motion Generation

In this section, we describe effects of reduced gravity on human motions and an efficient method of generating stable motions that can be well adapted to an environment with diverse, gravitational conditions. The key to generating adaptive motions is to find optimal gait properties under different gravitational conditions. We begin this section by explaining the relationship between gravity and bipedal movement.

4.1 Froude Number

A gait has a consistent pattern of movement, which is achieved through the movement of arms and legs. In the study of the mechanics of legged locomotion for a different gravitational condition, a gait pattern can be described using the Froude number.

The Froude number found by R. McN. Alexander [10] is a dimensionless parameter of the ratio between the centripetal force and the gravitational force for a legged creature. Thompson and Alexander defined the Froude number as:

$$F_r = \frac{mv^2/h}{mg} = \frac{v^2}{gh} = \frac{s^2 f^2}{gh}, \tag{1}$$

where m is the mass, h is the characteristic length, approximated by the leg length, s is the stride length, g is the gravity acceleration, v is the mean COM forward velocity, and f is the stride frequency, which is the number of strides in unit time. Two factors governing the forward speed v are stride length s and stride frequency f:

$$v = sf. \tag{2}$$

In other words, the forward speed can be increased either by moving legs faster, or by traveling further with each step.

The Froude number is always in the range of zero and one. If the Froude number is greater than one, which means that the centripetal force is greater than the gravitational force, the biped should float in the air. According to the empirical research, a biped switches from walking to running at $F_r = 0.5$, and the biped walks stably at $F_r = 0.25$ [2]. Based on these findings, we predict the biped movements caused by a level of gravity and design a method to generate natural motions.

We assume that we already know the leg length of our bipedal character model and the gravitational acceleration that our simulated environment has. Then, it is possible to calculate the Froude number about our motion under the Earth's gravity from Eq. (1). We assume that the Froude number we calculated in Earth's gravity is equal to the Froude number in altered gravity to satisfy dynamic similarity for the same gait dynamics. That is to say, the Froude number is constant regardless of different gravity for simulated motions.

4.2 Pre-estimation Model

We need two steps to simulate human motions in reduced gravity: setting up a low gravity environment and a pre-estimation model to predict gait patterns in a low gravity. Our physics-based control system generates animations based on the given captured reference motions including walking, running, and turning in Earth's gravity. Then, according to the level of gravity, we build a pre-estimation model to predict the COM forward velocity of our character as well as its stride frequency, and use them as a desired motion for the underlying control system, which will be explained in Sec. 5.

Our control system uses four gait variables to simulate motions, $M = \{\alpha_{leg}, \alpha_{vel}, \alpha_{stridefreq}, \alpha_{fpos}\}$, where α_{leg}, α_{vel}, $\alpha_{stridefreq}$, and α_{fpos} are, respectively, the variables for the leg length defined by our character, the forward velocity, the stride frequency, and the foot position at each motion phase such as swing or support phase. The forward velocity α_{vel} can be adjusted by scaling the forward velocity of a captured motion. Also, we can adjust the gait cycle duration $\alpha_{stridefreq}$ by altering the time scaling factor that determines the rate of the captured poses which are feed-forward. We build a pre-estimation model defined by these four gait variables and apply it to the control system, which will yield the results that are similar to the captured motions.

The Froude number is fixed according to the gait style of a captured motion and since the Froude number is constant regardless of the changed gravities, from Eq. (1), we calculate the velocity and the stride frequency of a bipedal motion:

$$v = \sqrt{F_r gh}, \tag{3}$$

$$f = \frac{\sqrt{F_r gh}}{s}. \tag{4}$$

As we know our character's leg length h and we assume that the stride length s is a constant regardless of the altered gravities to avoid excessively long or short stride, from Eqs.

(3) and (4), we get the ratio of the velocity and the stride frequency to gravity:

$$\frac{v_A}{v_B} = \frac{f_A}{f_B} = \sqrt{\frac{g_A}{g_B}}, \tag{5}$$

where A, B can be Earth, Mars, and the Moon, g_A and g_B are the gravities of A and B , v_A and v_B are the velocities on A and B, and f_A and f_B are the stride frequency on A and B. The velocity we calculated is set to the desired velocity for the simulated motion that we wish to construct. The calculated stride frequency is used for determining the timewarping ratio. The velocity and the stride frequency can be further adjusted manually when a different stride length is desirable to produce visually pleasing gaits without stumbling. One can also determine the optimal velocity and stride frequency for an arbitrary gravitational environment using the Froude number.

The motion planner produces limb motions based on the current estimated state of the pendulum and modifies the limb motions to make the resulting motions stable through the online optimization, to be explained in Sec. 5.1, that finds optimal joint torques and contract forces. The resulting full-body controller is further improved by modifying the feet trajectories using the offline optimization, to be explained in Sec. 5.2, because the online optimization alone may not create natural motions. Modifying the feet trajectories creates additional contact forces that change the simulated motion. Thus, the forward velocity of the simulated motion is determined by the desired velocity input to the pendulum model as well as these additional forces.

5 Physics-based Character Control using Optimization

Our control algorithm is formulated as an online optimization problem that is solved per-frame. The goal of the online optimization is to find the optimal joint torques and contact forces to control the model. At every frame, our controller adjusts the reference motion using a balance strategy presented by Kwon and Hodgins [5]. Short future horizon of the balance-recovering desired motion is instantaneously planned based on the estimated pendulum state. The motion of the full-body model is generated using a dynamics simulation that tracks the planned desired motion in an online manner.

5.1 Online optimization

The optimization step is formulated as a quadratic program using an objective function and a set of linear constraints, and computes joint torques τ, accelerations $\ddot{\mathbf{q}}$ and contact forces λ:

$$\min_{\tau, \ddot{\mathbf{q}}, \boldsymbol{\lambda}} L_{\text{tracking}} + L_{\text{end effector}} + L_{\text{torque}} + L_{\text{contact force}}, \tag{6}$$

subject to equations of motion and contact constraints.

5.1.1 Equations of Motion.

The equations of motion of the humanoid model is described as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) = \tau + \mathbf{J}_{\text{c}}^T \mathbf{f}_{\text{c}}, \tag{7}$$

where $\mathbf{q}$, $\dot{\mathbf{q}}$, and $\ddot{\mathbf{q}}$ are the generalized configuration of all degree-of-freedoms (DOFs) and its time-derivatives. $\mathbf{M}$ is the inertia matrix, and $\mathbf{c}$ combines the centrifugal, Coriolis and gravitational forces. Contact Jacobian matrix $\mathbf{J}_{\text{c}}$ maps the generalized velocity $\dot{\mathbf{q}}$ to the global velocities at the contact points. $\mathbf{f}_{\text{c}}$ contains the ground contact forces, represented as a linear combination of basis vectors of coulomb friction cones:

$$\mathbf{f}_{\text{c}} = \mathbf{V}_{\text{c}}\boldsymbol{\lambda}, \tag{8}$$

where $\mathbf{V}_{\text{c}}$ contains the basis vectors, and $\boldsymbol{\lambda}$ is a coefficient vector.

5.1.2 Contact constraints

Contact constraints are represented using a set of linear inequality constraints:

$$\boldsymbol{\lambda} \geq \mathbf{0}, \tag{9}$$

$$\mathbf{a}_c = \mathbf{V}_{\text{c}}^T \mathbf{J}_c \ddot{\mathbf{q}} + \mathbf{V}_{\text{c}}^T \dot{\mathbf{J}}_c \dot{\mathbf{q}} + \dot{\mathbf{V}}_{\text{c}}{}^T \mathbf{J}_c \dot{\mathbf{q}} \geq \mathbf{o}_c, \tag{10}$$

where Eqs. (9) and (10) represents the friction cones and the velocity cones, respectively. $\mathbf{a}_c$ denotes the global accelerations at contacts, and $\mathbf{o}_c$ denotes the velocity-dependent offsets at contacts [7].

The objective function for the per-frame optimization consists of four terms. All terms are in a quadratic form with respect to optimization variables $\ddot{\mathbf{q}}, \mathbf{a}$, and $\boldsymbol{\lambda}$.

5.1.3 Tracking objective

The tracking objective l_{tracking} minimizes the difference between the desired and the actual accelerations.

$$L_{\text{tracking}} = l_{\text{tr}} \|\ddot{\mathbf{q}}_{\text{d}} - \ddot{\mathbf{q}}\|^2, \tag{11}$$

where l_{tr} is the weighting factor for the tracking objective, $\ddot{\mathbf{q}}_{\text{d}}$ and $\ddot{\mathbf{q}}$ are the desired and the actual accelerations, respectively. We compute the desired acceleration based on the balance-recovering desired motion as follows:

$$\ddot{\mathbf{q}}_{\text{d}} = k_{\text{p}} f_{\text{diff}}(\mathbf{q}_{\text{r}}, \mathbf{q}) + k_{\text{d}}(\dot{\mathbf{q}}_{\text{r}} - \dot{\mathbf{q}}) + \ddot{\mathbf{q}}_{\text{r}}, \tag{12}$$

where $\mathbf{q}_{\text{r}}$, $\dot{\mathbf{q}}_{\text{r}}$ and $\ddot{\mathbf{q}}_{\text{r}}$ are the desired position, velocity and acceleration of all DOFs, and k_{p} and k_{d} are the gains.

5.1.4 End-effector objective

$L_{\text{end effector}}$ tries to track the desired end-effector positions and orientations in the cartesian space, because the foot-step location is critical for balancing.

$$L_{\text{end effector}} = l_{\text{ee}} \sum_i \|\ddot{\mathbf{y}}_{\text{d}}^i - \ddot{\mathbf{y}}^i\|^2, \tag{13}$$

where l_{ee} is the weighting factor for the end-effector objective, $\ddot{\mathbf{y}}_{\text{d}}^i$ and $\ddot{\mathbf{y}}^i$ are the desired and actual acceleration of the i^{th} end-effector.

5.1.5 Joint torques and contact forces

Minimizing joint torques and contact forces are important for obtaining smooth motions by reducing the impact from the ground. Also, these terms are necessary for making the objective function positive definite.

$$L_{\text{torque}} = l_{\text{torq}} \|\tau\|^2, \tag{14}$$

$$L_{\text{contactforce}} = l_{\text{cf}} \|\boldsymbol{\lambda}\|^2. \tag{15}$$

The weighting factors l_{torq} and l_{cf} are empirically chosen based on the trade-off between the stability of control and the motion smoothness.

5.2 Offline Optimization

Although the initial controller works successfully after careful tuning of the weighting factors, the controller is not optimal in terms of motion quality, and cannot generalize for environments with reduced gravity. For producing controllers that work in such environments, we first modify the forward velocity of the character and the duration of a gait cycle, and then employ a controller optimization technique proposed in [5]. This optimization process is robust enough that an initial controller that falls down in less than three steps was successfully optimized to produce the results in our experiments.

5.2.1 Forward Velocity and Gait Cycle

Based on the preview control of an inverted pendulum model, the forward velocity of the full-body character can be easily adjusted by changing the desired speed of the pendulum model. Because our controller uses the stride frequency of the captured reference motion by default, decreasing the forward velocity results in proportionally decreased stride. When unnecessarily long or short stride looks unnatural, we adjust the stride frequency by timewarping the captured reference motion. In our experiments, the forward velocity turns out to be a more important factor for robustness than the stride frequency. Thus, after we decide the forward velocity of the character using the Froude number, we adjust the stride frequency gradually from its calculated value based on Eq. 5 to naturally reproduce the observed behaviors of astronauts, for instance, on the Moon.

5.2.2 Optimization

Once the forward velocity and the stride frequency is fixed, we obtain a working controller by optimizing some of the input parameters to an initial controller. This optimization is performed in an offline preprocessing step for the first ten strides, and the resulting controller can robustly generate stable locomotion indefinitely. We optimize only the feet trajectories because the feet trajectories are the most important components for producing stable gaits, and do not modify the input parameters such as the forward velocity and the gait cycle. Assuming symmetric gaits, the dimensionality of the search space is 18, which corresponds to six three-dimensional control points for a foot displacement map, and the other foot uses the mirrored version of the displacement map. The same displacement map is used repetitively for all strides.

The offline optimization uses two objective terms to be simultaneously minimized. The first term, E_{pd}, penalizes the deviation of the simulated motion from the original reference motion:

$$E_{\mathrm{pd}} = \sum_{1}^{N} d_{\mathrm{pose}}(\mathbf{q}_{\mathrm{r}}, \mathbf{q}), \tag{16}$$

where N is the number of frames and d_{pose} measures the difference between the simulated pose and the corresponding pose of the time-warped reference motion. The pose

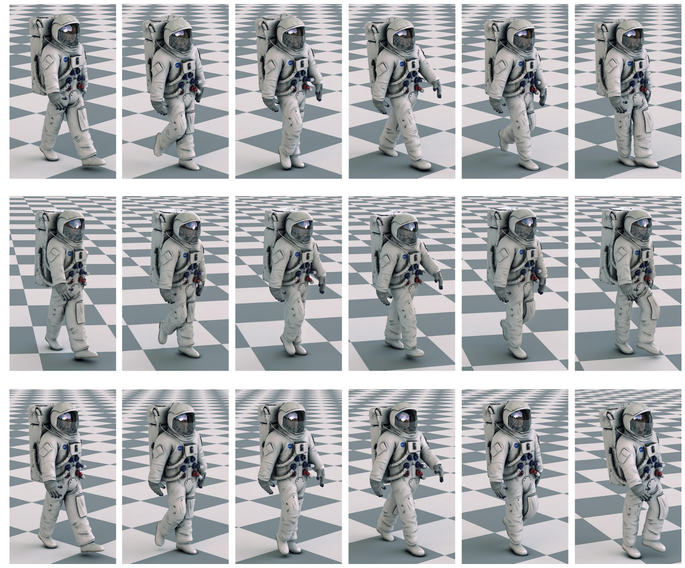


Fig. 2. Simulated walking motions in gravity of Earth, Mars, and the Moon from top to bottom rows, respectively.

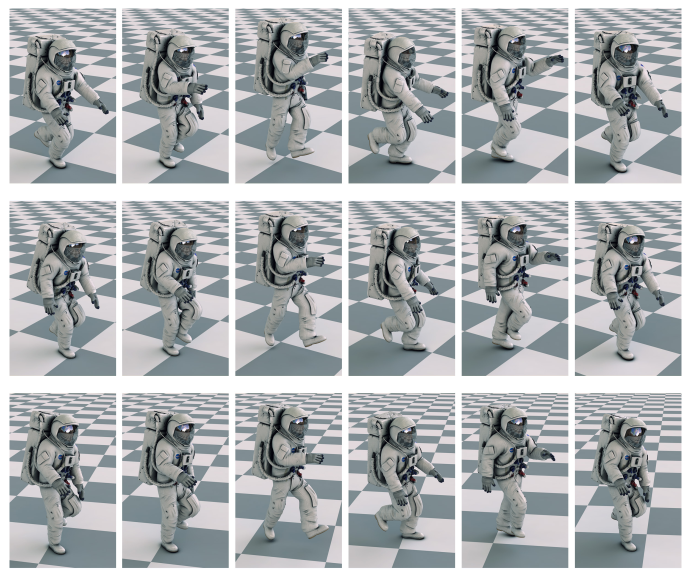


Fig. 3. Simulated running motions in gravity of Earth, Mars and the Moon from top to bottom rows, respectively.

difference is measured using point cloud matching about the vertical axis, and the height difference of the COM between the simulated and captured pose is ignored. This is because the character tends to jump higher when the gravity is significantly reduced. The second term, E_{sd}, measures the similarity between strides to produce steady motion:

$$E_{\mathrm{sd}} = \sum_{i=1}^{\mathrm{numstride}-1} \sum_{j}^{N_s} d_{\mathrm{pose}}(\mathbf{q}_{i,j}, \mathbf{q}_{i+1,j}), \tag{17}$$

where i denotes the i-th stride, and N_s represents the number of frames in a stride.

6 Results and Discussion

In this section, we show our simulation results and analyze them. We also compare our simulation results against those

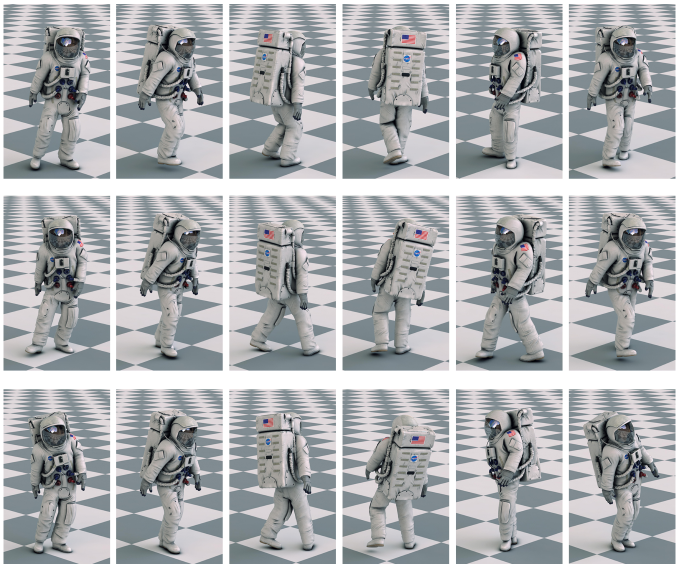
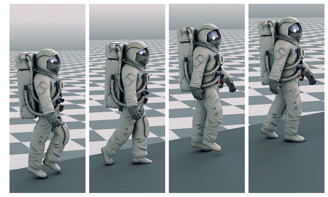
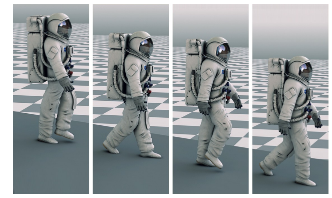


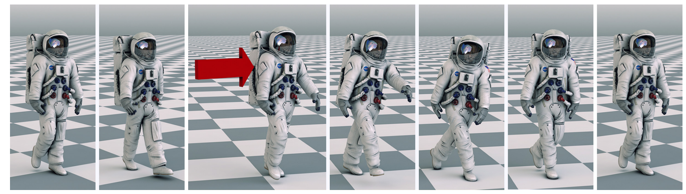
Fig. 4. Simulated turning motions in gravity of Earth, Mars, and the Moon from top to bottom rows, respectively.



(a) +5 $degrees$ inclined terrain



(b) -5 $degrees$ inclined terrain



(c) External force perturbations with 75 N for 0.2 sec

Fig. 5. (a), (b) Simulated walking motions in gravity of the Moon for inclined terrain of ± 5 degrees of inclination angle, and (c) with external force perturbation, denoted as the red arrow.

predicted by an analytical model as well as the video footages captured during the Apollo missions.

6.1 Experimental Results

We implemented our simulation system using Lua and C++ programming languages on a Mac Pro machine equipped with 3.5 GHz 6-Core Intel Xeon E5 and 16 GB memory under Mac OS X Yosemite. We used quadprog and the covariance matrix adaptation evolution strategy (CMA-ES) for online and offline optimization in our controller. The simulated full-body motion is rigged to an astronaut mesh-model and rendered. Figs. 2, 3, and 4 as well as the accompanying video show our simulation results including walking, running, and turning under the gravitational conditions of Earth, Mars, and the Moon, respectively. All the simulated motions show stable movements in reduced gravity. Our simulated character models have 39$\sim$54 DOFs, and their heights and masses range from 165 cm to 177 cm and from 62 kg to 77 kg, respectively. All DOFs of the models except the six DOFs at the root joint are actuated by joint torques. We use walking, running, and turning motions, captured in Earth's gravity, as reference motions for simulations.

Inclined Terrain We test the capability of our controller to move over inclined terrain in reduced gravity, where the inclination angle varies between $\pm$ 5 $degrees$. As also shown in the accompanying video, the character walks stably without losing its balance or falling down under the Moon's gravity. For 5 $degrees$ of inclination angle, the character slows down from 0.50 m/sec to 0.45 m/sec (Fig. 5 (a)). For -5 $degrees$ of inclination angle, the character speeds up from 0.50 m/s to 0.61 m/sec (Fig. 5 (b)).

External Perturbation Our controller can recover from external perturbations. In Fig. 5 (c), we demonstrate that our simulated character can walk stably in the gravity of the Moon when being pushed by unexpected external forces, that are equivalent to $75.0N$ for the duration of $0.2sec$. In this case, the character moves forward in balance due to the unexpected situation.

6.2 Analysis

We measure the average COM forward velocity, the stride frequency, and the stride length of our simulated characters, as shown in Table 1. The simulated motions show lower velocities and stride frequencies and shorter stride lengths in lower gravity except running motion, where we increase its velocity to maximum to create visually pleasing results.

We analyze the quality of simulation based on the Froude number. Fig. 6 shows graphs for the COM velocity with respect to different gravitational conditions. The used motion here is walking. The dotted line is a curve for the expected COM velocity, estimated from Froude number using Eq. (3) and the blue curve is a graph of our simulated results interpolated between the Moon's, Earth's and Mars' gravities. The result shows that our simulated results closely resemble the analytical one based on the Froude number.

In case of running motion, we did not make a comparison, as we set the velocity as high as possible regardless of the gravitational condition so that the velocities in different gravities are uniform, which gives more visually-pleasing results in our experiments. In case of turning motion, an analysis using Froude number is not very meaningful, as the motion contains rapid rotations and the forward velocity is not well defined.

Walking Motion The lower the level of gravity is, the higher the COM height becomes, as shown in Fig. 7 (a). As we set the COM forward velocity low in reduced gravity, the stride length becomes smaller and the period of walking motion becomes longer, as shown in Table 1. The duty factor gets similar to each other except the Moon's case, as shown in Fig. 8 (a). This difference is caused by the flight phases on the Moon. In case of the Moon, even if the character moves slowly with a small amount of joint torques, the character reacts to the ground reaction forces rather sensitively due to the reduced gravity, which causes a more frequent happening of flight phases. Specifically, although the ground reaction forces in Mars' and the Moon's case decrease by 70% and 83% compared to that of Earth, the flight phases occupies 30% of a walking cycle in the Moon's cases on average.

TABLE 1
Average COM forward velocity $\mathbf{v}$ in m/sec, average stride frequency in $1/sec$ and average stride length in m in our simulation under different gravity conditions.

Gravity	Walking			Running			Turning		
	$\mathbf{v}$	StFreq	StLen	$\mathbf{v}$	StFreq	StLen	$\mathbf{v}$	StFreq	StLen
Earth	1.28	0.89	1.44	0.97	0.93	1.05	0.70	0.85	0.82
Mars	0.80	0.74	1.08	1.10	0.63	1.75	0.58	0.66	0.87
Moon	0.50	0.52	0.96	1.09	0.54	2.05	0.51	0.66	0.78

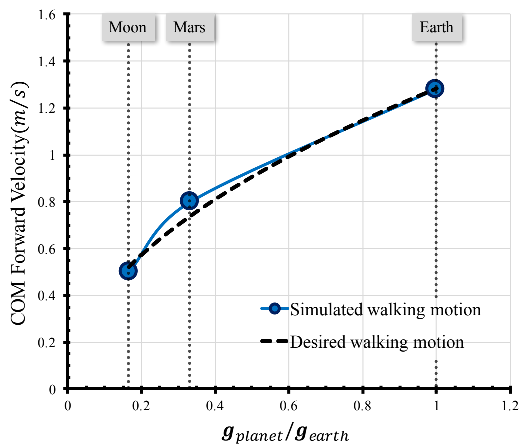
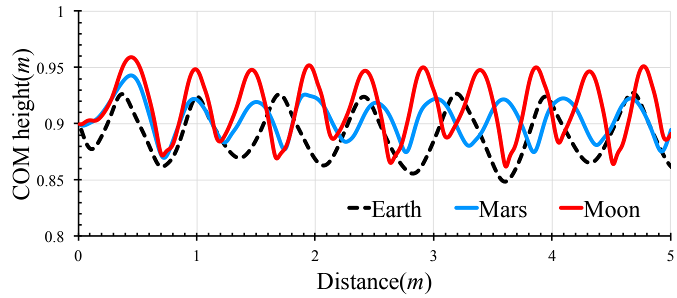
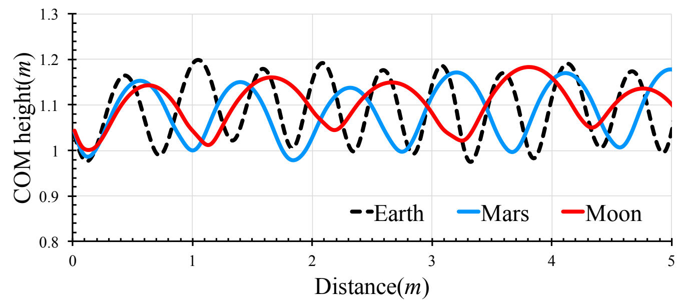


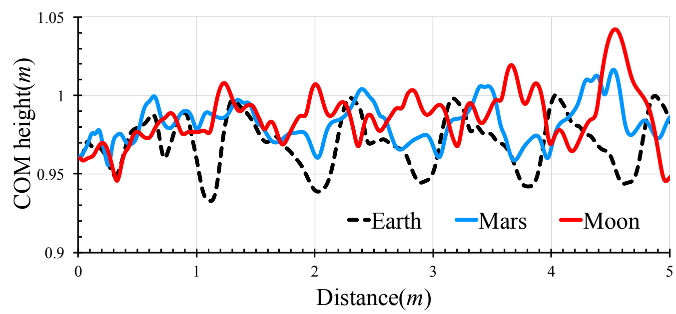
Fig. 6. Comparison against an analytical model using Froude number for walking motion. The x and y axes in the graph denote the normalized gravity with respect to the Earth's gravity and the COM forward velocity, respectively. The dotted line denotes a curve that is based on the analytical model using Eq. (3) and the blue line denotes a curve that is based on our simulation results. These curves show a similar pattern of results.



(a) Walking



(b) Running



(c) Turning

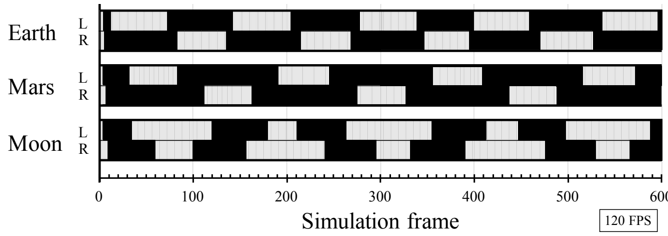
Fig. 7. COM height with respect to walking/running/turning distances in different gravities.

Running Motion As shown in Fig. 7 (b), the periodicity of the COM height for three different gravitational conditions is formed at around $1.08m$. At the same COM forward velocity, the smaller a level of gravity is, the longer the stride length becomes; see Table 1. The period of motion also becomes longer in lower gravity. The duty factors are similar to each other and the occurrences of flight phases for one running stride are also similar, as shown in Fig. 8 (b), but the ground reaction forces are different; the ground reaction forces in Mars' and the Moon's case decrease by 41% and 54% compared to that of Earth.

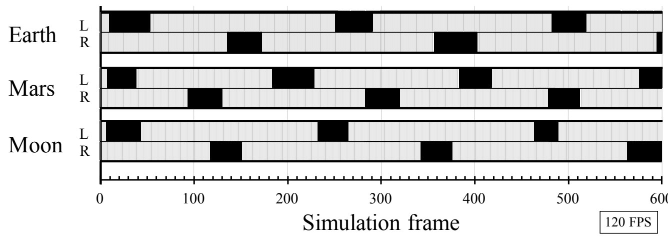
Turning Motion The COM trajectory of turning motion is regular, as the character balances itself on one stance hip while swinging the other leg. We set the COM forward velocity low when the gravity decreases. As the COM forward velocity lowers, the COM height becomes higher, as shown in Fig. 7 (c), and the turning radius of the COM trajectory becomes bigger starting from $1m$ to $2.5m$ and $3.5m$. As shown in Fig. 8 (c), the period of motion also increases in reduced gravity. Regardless of the velocity or gravity, the duty factor is almost unchanged. Although the ground reaction forces in Mars' and the Moon's case decrease by 65% and 80% compared to those in Earth, the flight phases occur more frequently than the cases of walking motions in reduced gravity.

6.3 Comparisons

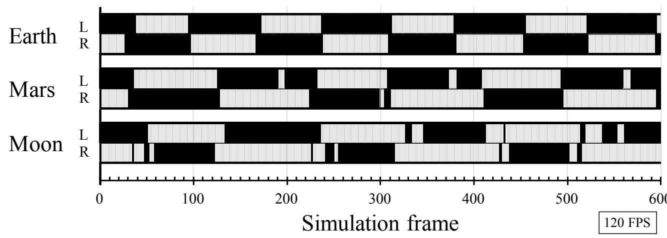
Quantitative Comparison against Ground Truth We quantitatively compare the similarity between our simulated motions and the real video footages of bipedal motions, that were captured by the NASA from the late 1960s to the early 1970s during the Apollo missions. In particular, we use the video clips provided by the NASA and available on the YouTube website (https://youtu.be/S9HdPi9Ikhk?t=54m21s). Here, the real motion starts from 54 minutes 21 seconds and last for 5 seconds in the video clip. We show the sequences of this live footage and of our simulated motion to compare each other in Fig. 9 (a) and (b). We also show



(a) Walking

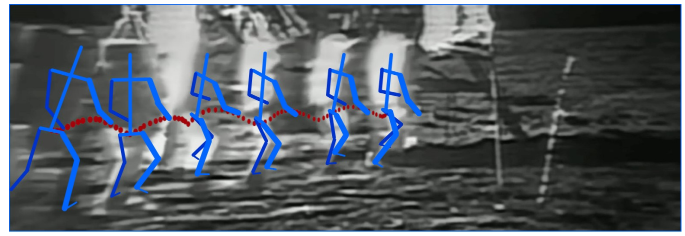


(b) Running

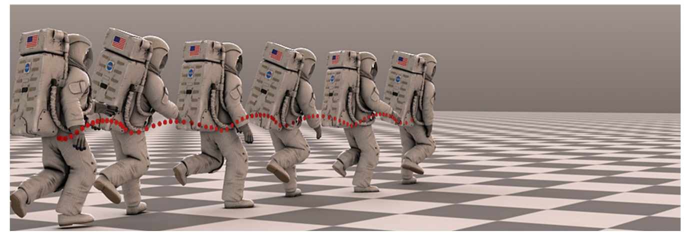


(c) Turning

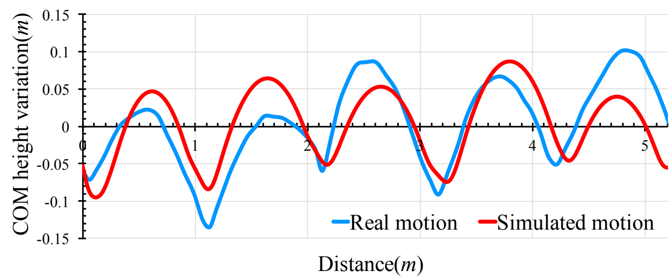
Fig. 8. Foot contact states with respect to simulation frame for walking/running/turning motions in different gravities. L is the left foot and R is the right foot. The contact phases are colored in black.



(a) The running astronaut motion, annotated with body skeletons in blue and the COM trajectory in red.



(b) Our simulated running motion in the Moon's gravity, annotated with the COM trajectory.



(c) COM height variation with respect to the run distance for the real and simulated motions.

Fig. 9. Comparison of our simulated running motion in gravity of the Moon against the Apollo 11 video footage.

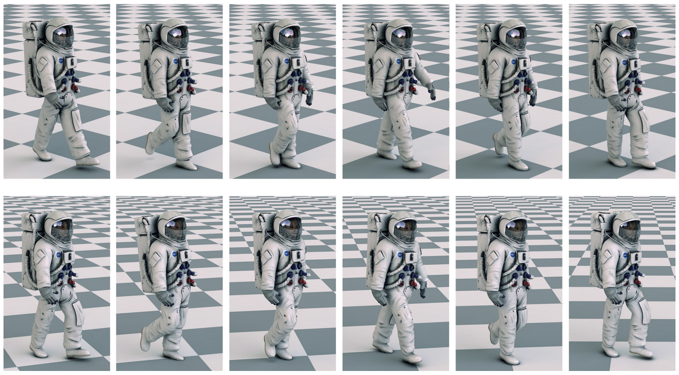
TABLE 2
Average COM forward velocity $\mathbf{v}$ in m/sec, average stride frequency in $1/sec$ and average stride length in m for the real astronaut motion and our simulated running motion under the Moon's gravitational condition.

	$\mathbf{v}$	StFreq	StLen
Real motion	1.08	0.57	2.01
Simulated motion	1.09	0.54	2.05

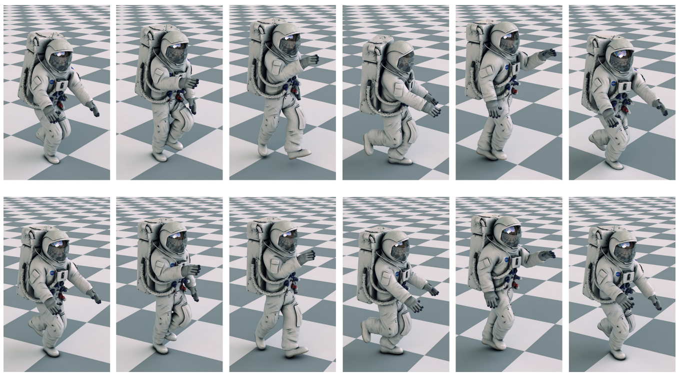
the COM trajectories for both simulated motion and real astronaut motion in Fig. 9 (c). According to this experiment, the COM forward velocity, the stride frequency, and the stride length have only about 1$\sim$5% relative differences, even considering the fact that the simulation environment is only approximate to the Apollo mission. Our simulated motion visually matches with these ground truth sequences as well. We also show these comparisons in the accompanying video.

Qualitative Comparisons against Existing Methods Geijtenbeek et al. presented a muscle-based controller for the simulated locomotion of various 3D bipedal creatures [11]. Based on an SIMBICON-style balance correction and an optimization strategy, the method produces robust locomotion at given speeds and the amount of gravity. Muscle-based control allowed a more accurate estimation of the energy expenditure at the expense of complex modeling process and increased number variables to control. Because the approach in [11] does not rely on any reference motion data, it has the advantage to find an optimal stride frequency that minimizes energy estimates. On the other hand, the resulting frequency can be very different from real-world observations because of the model discrepancy. Estimating the model parameters of a high-dimensional system from real-world observations is a much harder problem to solve, and is an open research area. Our approach takes a different approach to obtaining controllers. Our controller is created from a reference motion captured on Earth, and adapted to generate new gait behaviors in reduced gravity. Our control algorithm is chosen because it allows convenient control of the stride frequency. Omer and colleagues conducted a study on humanoid walking at different gravity levels using a mass/spring model with ZMP-based control [12]. However, it is unclear whether these techniques are applicable to human locomotion with different gait styles including running or turning. Also, these approaches do not provide a direct way to control the stride frequency of the simulated gaits.

We build our controller based on a tracking algorithm proposed by Kwon and Hodgins [5], and employed by other researchers. Their controller is based on the common idea of preview control of inverted pendulum models. However, the inverted pendulum on a cart (IPC) controller proposed in [5] differs in that it plans a smooth pendulum trajectory that follows only the center of mass of the character, and it is not constrained to follow the center of pressure of the feet.



(a) Walking



(b) Running

Fig. 10. Simulated walking and running motions in gravity of Neptune (top rows in (a) and (b)) and Jupiter (bottom rows in (a) and (b)).

This is because the IPC model is geometrically mapped to a full-body human pose. Without explicit constraints on the center of pressure, the control algorithm for the IPC model is contact-independent. We adopt the same IPC controller because this property enables easy manipulation of stride frequency and contact timing which is critical for simulating locomotion at different gravity as we experimentally show. Motivated by these work, we also use a combination of the IPC model for motion planning, QP for per-frame tracking, and an offline controller optimization. Our goal differs in that we generalize a reference motion to the completely different environments of Mars and the Moon.

6.4 Extension to Higher Gravity

In order to test the generality of our system, we simulate that the character walks and runs in higher gravities such as Neptune and Jupiter. Neptune and Jupiter's gravity are 1.14 and 2.53 times higher than the Earth's gravity, respectively. In this case, we first set the COM forward velocity properly using our pre-estimation model. As shown in Fig. 10, the character moves stably in higher gravity. In particular, as shown in the accompanying video, in case of walking motion, the higher the level of gravity is, the lower the COM height becomes. In Table. 3, the stride length in Neptune's and Jupiter's cases becomes shorter from 1.44 m to 1.11 m and 1.09 m, and the period of walking motion becomes shorter as well.

TABLE 3
Average COM forward velocity $\mathbf{v}$ in m/sec, average stride frequency in $1/sec$ and average stride length in m in our simulation under the higher gravitational conditions.

Gravity	Walking			Running		
	$\mathbf{v}$	StFreq	StLen	$\mathbf{v}$	StFreq	StLen
Neptune	1.25	1.12	1.11	1.07	0.89	1.20
Jupiter	1.32	1.21	1.09	0.90	0.80	1.12

7 Conclusion

In this paper, we have proposed a new physics-based approach to simulate the full-body human locomotion in reduced gravity. Our approach uses a pre-estimation model based on the Froude number to predict the desired velocity of our character model in hypogravity, and the full-body animation is generated by a sequence of IP generation, motion planning and tracking. In our experiments, we successfully demonstrate that our simulation can generate stable and robust full-body animation of various gaits under different gravitational conditions. For future work, which is also a limitation of our current work, we would like to design a control system that can generate walk-run transition motion and predict gait pattern changes according to reduced gravity.

Acknowledgment

Young J. Kim is the corresponding author. This project was supported in part by the NRF in Korea (2014K1A3A1A17073365, 2015R1A2A1A15055470). Taesoo Kwon was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (MSIP) (NRF-2014R1A1A1038386).

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Yun-hyeong Kim is a MS student in computer science and engineering at Ewha Womans University. She received her BS in computer science and engineering from Ewha Womans University. Her research interests include physics-based animation, robotics, and computational geometry.

Taesoo Kwon is a professor of computer science at Hanyang University since 2012. He also leads a computer animation research group. His research interests center on improving the design and performance of animation techniques, mainly through the application of physics-based models and machine learning techniques

Daeun Song is a MS student in computer science and engineering at Ewha Womans University. She received her BS in computer science and engineering from Ewha Womans University. Her research interests include robotics, interactive computer graphics and computational geometry.

Young J. Kim is a full professor of computer science and engineering at Ewha Womans University and an Ewha fellow. He received his PhD in computer science from Purdue University, and was a postdoctoral research fellow at the University of North Carolina at Chapel Hill. His research interests include interactive computer graphics, computer games, robotics, haptics, and geometric modeling.