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Active balancing and turning for alpine skiing robots

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Abstract

This paper presents our preliminary research into the autonomous control of an alpine skiing robot. Based on our previous experience with active balancing on difficult terrain and developing an ice-skating robot, we have implemented a simple control system that allows the humanoid robot Jennifer to steer around a simple alpine skiing course, brake, and actively control the pitch and roll of the skis in order to maintain stability on hills with variable inclination.

The robot steers and brakes by using the edges of the skis to dig into the snow, by inclining both skis to one side the robot can turn in an arc. By rolling the skis outward and pointing the toes together the robot creates a snowplough shape that rapidly reduces its forward velocity.

To keep the skis in constant contact with the hill we use two independent proportional-integral-derivative (PID) controllers to continually adjust the robot's inclination in the frontal and sagittal planes.

Our experiments show that these techniques are sufficient to allow a small humanoid robot to alpine ski autonomously down hills of different inclination with variable snow conditions.

1 Introduction and motivation

As research into humanoid robotics advanced we have seen the development of highly specialised forms of locomotion including climbing (Wickrath, 2010; Iverach-Brereton, 2014) and ice skating (Iverach-Brereton *et al*., 2012a, 2012b). While the ability to traverse extremely rugged terrain with unknown traction and rigidity remains beyond the state-of-the-art for humanoid robotics, research into specialised forms of locomotion remains a useful tool towards the development of a robust, general-purpose humanoid robot.

Alpine skiing offers unique challenges for humanoid robots. Snow offers a wide range of properties depending on weather conditions. Cold and dry temperatures produce light, fluffy snow that has little initial rigidity but can be compacted underfoot. Warm and humid conditions produce snow with a heavy, sticky quality that resists compression, but offers high gliding resistance.

This paper presents our preliminary work on the development of a three-dimensional control system for balancing a robot while alpine skiing. The remainder of this paper is divided as follows.

Section 2 provides a survey of previous research into alpine skiing robots, as well as previous research into active balancing on unstable terrain.

Section 3 summarises the construction of the robot's skis and poles, as well as the physical properties of the robot used in this research.

Section 4 describes how we adapted our previous research into active balancing on a bongo board (Baltes *et al*., 2013, 2014; Iverach-Brereton, 2015a) for use in stabilising the robot as it skis across hills of varying inclination in the frontal and sagittal planes.

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Section 5 described the motions the robot uses for braking and steering when alpine skiing. By exploiting the way the edges of the skis carve into the snow the robot can turn in arcs to either side as well as brake by bringing the toes of the skis together.

Section 6 describes the physical properties of various snow conditions experienced during our research and the impact they had on our experiments.

Finally, in Section 7 we draw conclusions and discuss future applications of this research.

2 Related work

Balancing is central to most tasks involving humanoid robotics, the humanoid body naturally forms an unstable inverted pendulum with the fulcrum located at the zero moment point (ZMP) in the robot's feet and the mass located at the robot's centre of mass (CoM, typically located somewhere within the robot's torso), as shown in Figure 1 (Sugihara *et al.*, 2002). This unstable arrangement necessitates either large feet with strong leg and ankle motors able to produce a statically stable state, or active control to produce a dynamically stable system.

While modern humanoid robots are able to traverse flat ground with high traction (e.g. concrete, thin carpet, hardwood) with ease, traversing unstable or slippery terrain (e.g. debris fields, ice) remains very difficult (Iverach-Brereton *et al.*, 2012a, 2012b; Iverach-Brereton, 2015a). In 2012, Iverach-Brereton *et al.* showed that a walking gait based on the linear inverted pendulum model could be modified to allow a small humanoid robot to traverse ice when equipped with skates (Iverach-Brereton *et al.*, 2012a, 2012b).

Gaits based on the inverted pendulum model consist of two distinct phases: the double support phase (DSP), during which both feet are on the ground and the robot is in a statically stable position, and the single support phase (SSP), during which one foot is in contact with the ground and the other leg swings forward. During the SSP the robot is unstable, the robot effectively falls forward, rotating around the support leg. The swing leg is brought forward to arrest the robot's falling, starting a new DSP (Baltes & Lam, 2004). Figure 2 shows keyframes from a dynamically stable walking gait used by a small humanoid robot.

When traversing uneven terrain the transition between SSP and DSP may occur at uneven intervals, changes in ground elevation can cause the swing leg to strike the ground earlier or later than expected. On generally level ground with good traction this does not cause problems. But when presented with uneven ground (e.g. slopes, stepping fields) the gait can become unstable (Chen & Byl, 2012). The use of phase modification based on gyroscope data has been shown to mitigate this problem and allow the robot to walk across small changes in elevation without falling over (Baltes & Lam, 2004; McGrath *et al.*, 2004; Adiwahono *et al.*, 2010; Yi *et al.*, 2011).

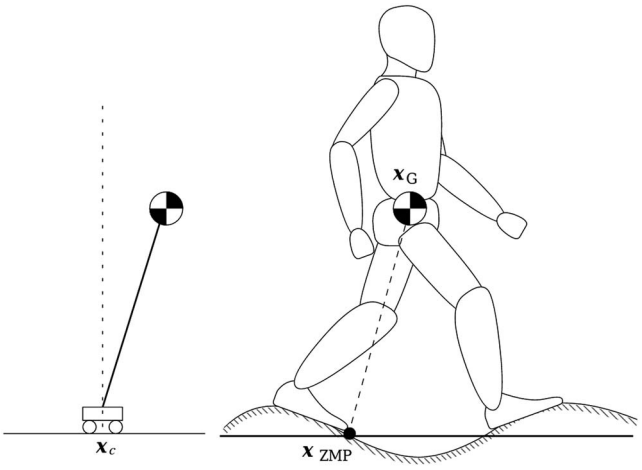


Figure 1 An inverted pendulum (left) and a humanoid system (right) showing the fulcrum, rod, and mass of the pendulum (Sugihara *et al.*, 2002). ZMP = zero moment point

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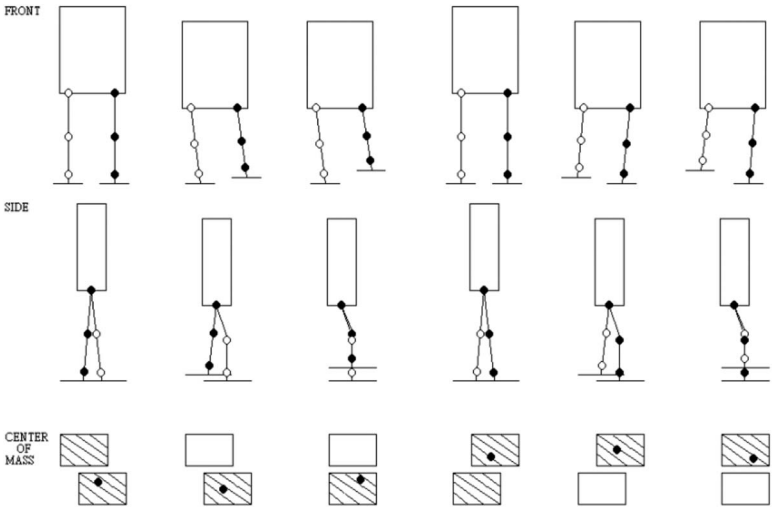


Figure 2 The walking gait used by a simple humanoid robot, showing the single support and double support phases (Baltes & Lam, 2004)

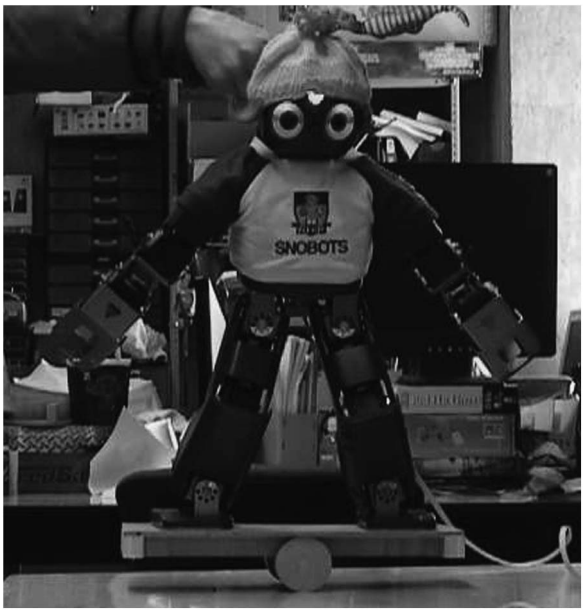


Figure 3 Jimmy, a DARwIn-OP humanoid robot, on a bongo board (Baltes *et al*., 2014)

While phase modification is adequate to address the problems of active balancing on uneven terrain, dynamic terrain—terrain where the inclination and elevation are not constant from moment-to-moment—remains problematic. Baltes *et al*. (2014) showed that PID controllers were able to stabilise a humanoid robot on a bongo board. Iverach-Brereton (2015a) further demonstrated that fuzzy logic controllers were suitable for this task.

The bongo board is a simple example of highly dynamic terrain, the robot must stand on a flat deck positioned above a free-rolling, cylindrical wheel, as shown in Figure 3. By controlling the rotation of each arm at the shoulder, translating the hips vertically and horizontally, and inclining the torso to the left and right the robot is able to keep the deck level and keep the CoM of the system positioned above the wheel, keeping the bongo board system stable (Baltes *et al*., 2014; Iverach-Brereton, 2015a).

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Figure 4 Jennifer, the robot used in this research, equipped with wooden skis and ski poles. The insulated shirt, helmet, and trousers helped protect the robot from cold and moisture (Martin, 2015)

Skiing humanoid robots are a relatively new area of research. While some researchers have begun looking at the problems of alpine skiing, including Lahajnar *et al.* (2009), Petrič *et al.* (2011), and Nemec and Lahajnar (2009), there remains much research to do in the area.

The majority of research into alpine skiing has focussed on balance and turning. Jentschura and Fahrbach (2004) provide equations defining a mathematically ideal carving turn. Nemec and Lahajnar (2009) similarly focus on directional control using the carving technique.

Petrič *et al.*'s work (2011) by contrast focusses on balancing the robot. Their system's primary goal is to control the robot's balance, with directional control as a secondary goal, and finally controlling the robot's pose.

Nemec and Lahajnar (2009) combine balancing and turning to produce a lower-body humanoid robot equipped with carving skis. Their robot uses a proportional-derivative (PD) controller to monitor and adjust the robot's acceleration and torso inclination, and was able to actively avoid obstacles on unknown ski hills.

3 Hardware used

Jennifer[1], the robot used for this research, is a standard DARwIn-OP robot manufactured by Robotis (Robotis, 2012), shown in Figure 4. The robot was modified from its stock configuration by the addition of single d.f. hands. Jennifer stands ~45 cm tall with a mass of 2.9 kg. Because we conducted our research outdoors on natural snow, we equipped the robot with an insulated shirt, trousers, and helmet to help protect the robot from cold and moisture.

The robot's skis, shown in detail in Figure 5, are made of spruce wood ~4 mm thick. The ends of the skis were steam bent into the upward curve. Unlike more modern 'carving skis'—first introduced in the 1980s and popularised during the 1990s (Petrič *et al.*, 2011), shown in Figure 6—which feature wider lobes at the nose and tail of the ski with a thinner midsection, Jennifer's skis are traditional, straight-sided skis. Carving skis provide more efficient control when turning by reducing skidding (Jentschura & Fahrbach, 2004; Petrič *et al.*, 2011) but for the purposes of our initial research we chose to use the simpler-to-manufacture traditional skis.

[1] Jennifer is named after Canadian women's ice hockey Olympic Gold Medalist and world champion Jennifer Botterill.

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Figure 5 A detailed view of the skis used in this research. The skis are made out of spruce wood cut ~4 mm thick with steam-bent tips. The skis are attached to the underside of the robot's foot with counter-sunk screws to provide a smooth running surface

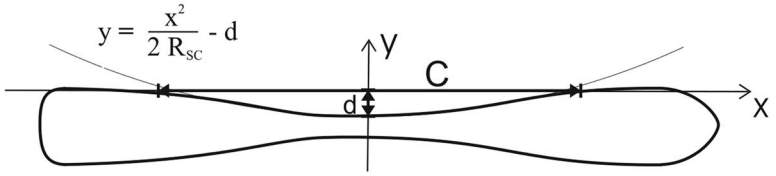


Figure 6 A typical carving ski. The ski's tip is to the right. The two-lobed shape is produced by circular cutouts along each side of the ski. The radius of these cutouts is R_{SC}, while the depth of the cutout relative to the edge of the ski is given by d. Traditional skis with straighter sides have a smaller d and larger R_{SC} (Jentschura & Fahrbach, 2004)

4 Active balancing

Like Lahajnar *et al*. (2009) and Nemec and Lahajnar (2009), we use a PD controller to adjust the robot's torso inclination to ensure that the skis remain in contact with the hill at all times while keeping the torso upright and the CoM centred over the feet. Unlike this system however, we do not focus exclusively on lateral stability, our system actively balances on both the frontal and sagittal planes. In addition, our control model is much simpler, employing only two PD controllers without the need for ZMP calculations.

Our control system is based on the 'Do the Shake' control policy published by Baltes *et al*. (2014). The 'Do the Shake' policy uses a linear predictive model to extrapolate the robot's current inclination based on previous readings from the robot's three-axis accelerometer. We use the following control law to adjust the robot's inclination, θ in both the frontal and sagittal planes:

$$\begin{aligned} \theta' &= \text{predicted}\,(\theta_{\text{torso}},\ \dot{\theta}_{\text{torso}}) \\ \theta &= K_p \cdot \theta' + K_d \cdot \dot{\theta}' \end{aligned} \tag{1}$$

where θ_{torso} and $\dot{\theta}_{\text{torso}}$ are the latest sensor readings giving the torso's inclination and angular velocity, respectively. Because of latency in processing the sensor data these readings represent the robot's state

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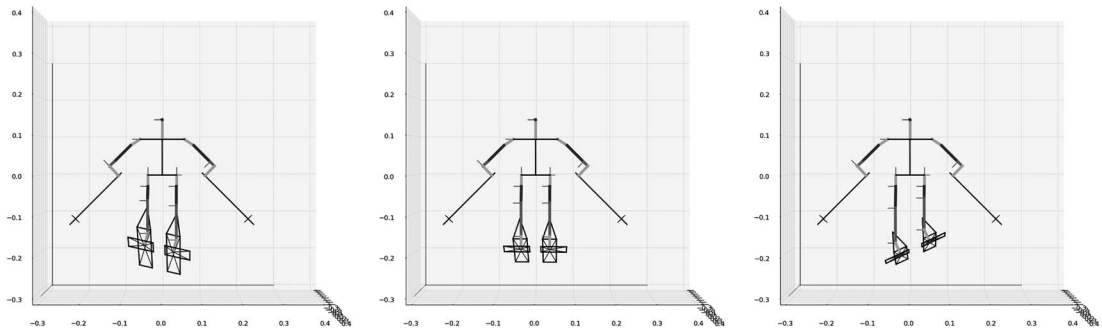


Figure 7 The robot's pose being adjusted for changes in inclination in the frontal plane. Note how the torso inclination is adjusted by raising and lowering the legs

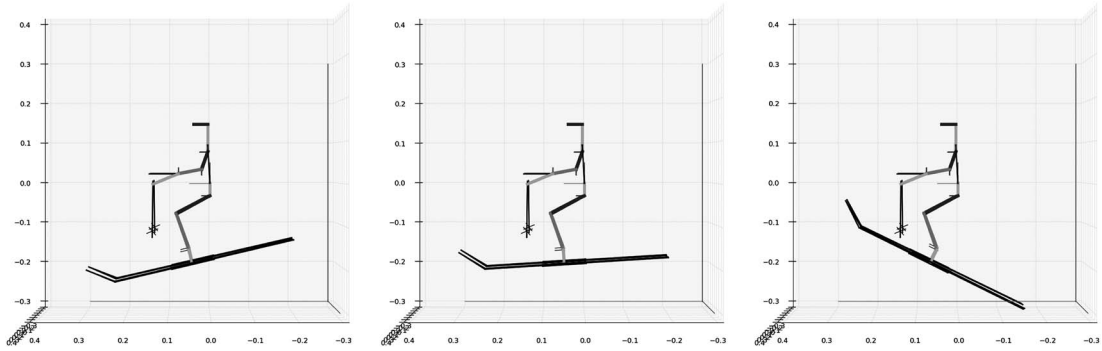


Figure 8 The robot's pose being adjusted for changes in inclination in the sagittal plane. The robot uses its ankles to control the pitch of the skis and keep the torso upright

several milliseconds earlier than its actual current state. θ' is the robot's estimated real-world current torso inclination, derived by applying a linear predictive model to the sensor readings to compensate for this latency. θ the desired output torso angle of the system. K_p and K_d the proportional and derivative gains of the PD controller, respectively.

We use two independent PD controllers, one to compensate for motion in the frontal plane and one to compensate for motion in the sagittal plane. This allows the robot to keep its skis flush with the ground and its torso upright regardless of the inclination of the ground below it. A video of the robot compensating for changes in inclination can be found on YouTube (Iverach-Brereton, 2015b).

To control the inclination in the frontal plane the robot adjusts the length of each leg by extending or contracting the knee, as shown in Figure 7. The ankles rotate in the frontal plane to ensure that underside of the skis stay in the same plane, as can be seen in Figure 8.

To control inclination in the sagittal plane the robot relies entirely on its ankle motors. In order to keep the skis parallel to one another we dynamically control the transverse motors located in the robot's hips based on the width of the robot's stance and the inclination of the ankles.

During outdoor trials with variable snow conditions this simple PID control system was able to keep the robot upright despite uneven snow and variable inclination slopes.

5 Alpine skiing control

As shown by Jentschura and Fahrbach (2004), an ideal alpine skiing turn can be achieved by using the edge of the ski to dig into the snow, forcing the skier to move in an arc. As noted by Jentschura and Fahrbach, carving skis are required for an optimal turn. However, straight-sided traditional skis can still carve, albeit sub-optimally.

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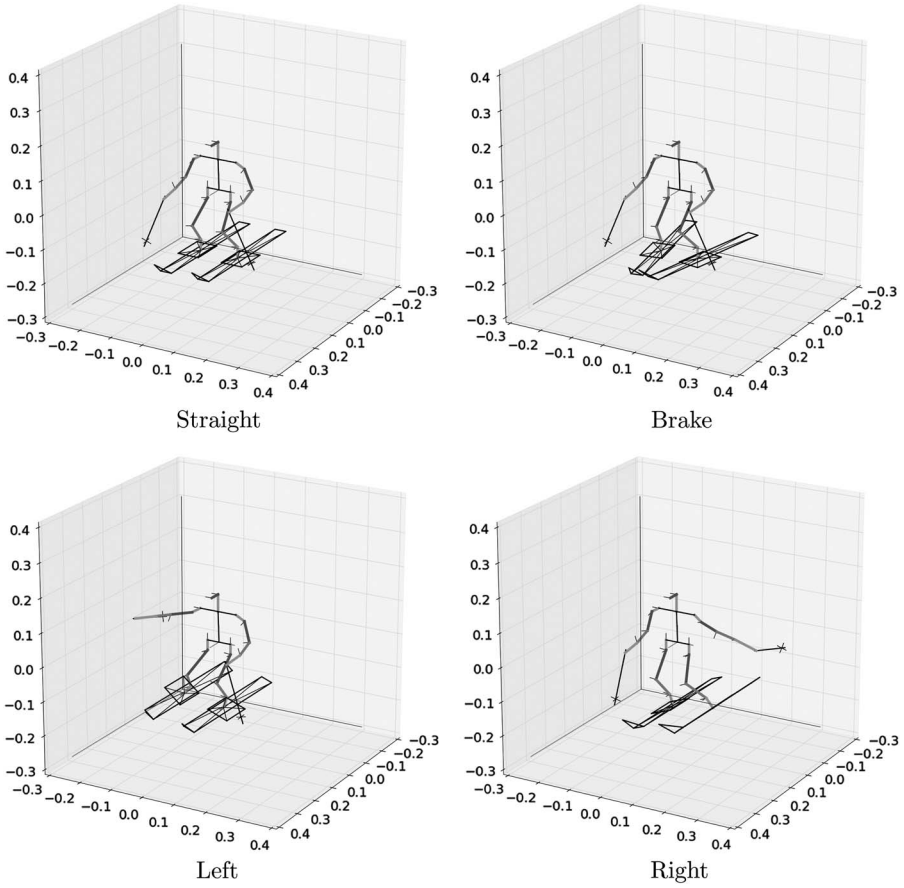


Figure 9 The robot's pose when skiing straight down the hill, braking, turning left, and turning right

Our alpine skiing system defines four main states for the robot: skiing straight, braking, turning left, and turning right. Poses representative of these states can be seen in Figure 9.

When skiing straight the robot keeps the bottoms of the skis flush with the snow and keeps the edges of the skis parallel with each other. This minimises resistance, allowing the robot to reach higher speeds when going down the slope.

To reduce forward velocity the robot turns the points of the skis inward and rolls the edges of the skis outward, forcing the inside edges of the skis to dig into the snow. This V-shape acts like a snowplough, creating high resistance and rapidly decelerating the robot. The degree to which the robot turns the skis can be controlled dynamically, ranging from a very slight angle to introduce minimal braking to the extreme V-shape shown in Figure 9.

The carving turn is accomplished by shortening the leg on the inside of the turn (by contracting the knee), and rotating both ankles in the frontal plane such that the edges of the ski towards the inside of the turn are both lowered. In addition, the robot translates its torso laterally such that the CoM lies above the inside ski. The outward arm is extended to provide balance, while the inside arm is brought inward.

As with braking, the amplitude of the turn can be controlled by adjusting the degree to which the torso is translated and the ankles are rolled. In practice, this allowed the robot to perform short, abrupt turns as well as long, arcing turns.

To test the control we marked a section of the hill with blue and pink markers. The robot was programmed to ski down the hill, staying within the marked area. Blue markers indicate the left side of the course and pink markers indicate the right. If the robot starts to veer out of bounds it will steer using the carving technique towards the centre of the course (i.e. it will steer right to avoid blue markers and left to avoid pink markers). After passing all the markers the robot assumes the braking position to stop at the bottom of the hill. A picture of the robot navigating the course is shown in Figure 10.

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Figure 10 Jennifer navigating a simple skiing course. The robot is programmed to ski within the area marked by the markers to avoid going out of bounds

A video showing our robot actively steering around the obstacles in our experiment is available on YouTube (Iverach-Brereton, 2015c).

6 Snow conditions

Any outdoor winter sport, including ice skating and skiing, is subject to the current weather conditions. A skier's ability to glide down a hill quickly, steer, and brake are all impacted by the depth and quality of the snow on the hill. Snowfall, temperature, and humidity all impact the snow conditions. As our testing was done outside in an uncontrolled environment over the course of several weeks ranging from mid-winter to early spring we encountered a wide range of environmental conditions.

Our previous research into ice skating (Iverach-Brereton *et al.*, 2012a, 2012b) showed that weather conditions dramatically changed the properties of the outdoor skating rink used for testing. When the temperature was well below freezing the ice was hard and dry, providing a very low-friction surface that maximised the robot's ability to glide on the ice. When the temperature was closer to freezing the surface of the ice became wet and sticky, increasing traction and reducing the robot's ability to glide.

Snow behaves similarly to ice, higher temperatures and humidity result in a higher liquid water content in the snow, resulting in heavier, stickier snow. Drier, colder conditions result in lighter, fluffier, powdery snow (ICSI-UCCS-IACS Working Group on Snow Classification, 2009).

During our research we discovered that the properties of the snowpack—the deep layer of snow that accumulates over the winter—was particularly important. Because the robot we used is fairly small (~45 cm tall and 2.9 kg mass) it could not ski well through loose snow deeper than 2–3 cm. Snow deeper than this would pile up on and in front of the skis, inhibiting the robot's forward progress.

During early spring the top of the snowpack would melt over the course of the day when the temperature rose to near-freezing, but would freeze again overnight when the temperature dropped. This thaw–freeze cycle produced a hard, brittle, icy layer of snow that adequately supported the robot's weight and provided nearly ideal conditions for the robot to ski on. A thin layer of light, powdery, dry snow on top of the icy snowpack was found to be optimal, the lighter fresh snow gave the robot's skis better traction when braking and turning, while still benefiting from the support of the icy snowpack.

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7 Conclusions and future work

This work represents the early stages of our research into humanoid alpine skiing robots. Because alpine skiing requires snowy conditions we are currently working on adapting our algorithms to use roller skis such that our research can continue during the summer months. Our early experiments with roller skis indicate that wheels are not suitable for carving turns, necessitating a new approach to steering when going down inclined surfaces.

Other areas of future research include implementing a system to allow the robot to dynamically switch between cross-country and alpine skiing modes depending on the inclination of the ground. The robot would use a cross-country gait, based on the linear inverted pendulum model, to traverse flat and uphill portions of the course, and switch to alpine skiing for steep downhill portions.

Nonetheless, this research has shown that a simple two-axis PD control system is suitable for balancing a humanoid robot when alpine skiing. Furthermore, we have shown that such a robot equipped with straight-edged skis can use carving turns to navigate simple alpine obstacle courses.

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References

Adiwahono, A. H., Chew, C.-M., Huang, W. & Dau, V. H. 2010. Humanoid robot push recovery through walking phase modification. In *Proceedings of the IEEE Conference on Robotics, Automation and Mechatronics (RAM 2010)*, June, 569–574.

Baltes, J., Iverach-Brereton, C. & Anderson, J. 2013. Sensor filtering for balancing of humanoid robots in highly dynamic environments. In *Automatic Control Conference (CACS), 2013 CACS International*, December, 170–173.

Baltes, J., Iverach-Brereton, C. & Anderson, J. 2014. Human inspired control of a small humanoid robot in highly dynamic environments or Jimmy Darwin rocks the bongo board. In *Presented at the RoboCup 2014 Symposium*, pending publication.

Baltes, J. & Lam, P. 2004. Design of walking gaits for tao-pie-pie, a small humanoid robot. *Advanced Robotics* **18**(7), 713–716.

Chen, M.-Y. & Byl, K. 2012. Analysis and control techniques for the compass gait with a torso walking on stochastically rough terrain. In *Proceedings of the 2012 American Control Conference (ACC 2012)*, 3451–3458.

ICSI-UCCS-IACS Working Group on Snow Classification 2009. *The International Classification for Seasonal Snow on the Ground*. UNESCO. `http://unesdoc.unesco.org/images/0018/001864/186462e.pdf`.

Iverach-Brereton, C. 2014. Dynamic ladder climbing, 8 October. `https://youtu.be/s-81_wL-YJQ`.

Iverach-Brereton, C. 2015a. *Rocking the Bongo Board: Humanoid Robotic Balancing on Dynamic Terrain*. Master's thesis, University of Manitoba.

Iverach-Brereton, C. 2015b. Active balancing for alpine skiing, 6 February. `https://youtu.be/NxDfWx_4ywc`.

Iverach-Brereton, C. 2015c. Jennifer Darwin carves the slopes, 28 May. `https://youtu.be/XU17sbItYxI`.

Iverach-Brereton, C., Baltes, J., Anderson, J., Winton, A. & Carrier, D. 2012a. Gait design for an ice skating humanoid robot. *Robotics and Autonomous Systems* **62**(3), 306–318.

Iverach-Brereton, C., Winton, A. & Baltes, J. 2012b. Ice skating humanoid robot. In *Advances in Autonomous Robotics*, Herrmann, G., Studley, M., Pearson, M., Conn, A., Melhuish, C., Witkowski, M., Kim, J.-H. & Vadakkepat, P. (eds), Lecture Notes in Computer Science **7429**, 209–219. Springer Berlin/Heidelberg.

Jentschura, U. D. & Fahrbach, F. 2004. Physics of skiing: the ideal carving equation and its applications. *Canadian Journal of Physics* **82**(4), 249–261.

https://doi.org/10.1017/S0269888916000163 Published online by Cambridge University Press

Lahajnar, L., Kos, A. & Nemec, B. 2009. Skiing robot – design, control, and navigation in unstructured environment. *Robotica* **27**(4), 567–577.

Martin, N. 2015. Robot goes from hockey skates to skis. *Winnipeg Free Press*, 2 February, A2.

McGrath, S., Baltes, J. & Anderson, J. 2004. Active balancing using gyroscopes for a small humanoid robot. In *Second International Conference on Autonomous Robots and Agents (ICARA)*, Mukhopadhyay, S. C. & Gupta, G. S. (eds). Massey University, 470–475.

Nemec, B. & Lahajnar, L. 2009. Control and navigation of the skiing robot. In *Intelligent Robots and Systems, 2009. IEEE/RSJ International Conference on IROS 2009*, October, 2321–2326.

Petrič, T., Nemec, B., Babic, J. & Zlajpah, L. 2011. Multilayer control of skiing robot. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, September, 4832–4837.

Robotis 2012. DARwIn-OP: Robotis. `http://www.robotis.com/xe/darwin_en` (accessed 19 April 2012).

Sugihara, T., Nakamura, Y. & Inoue, H. 2002. Realtime humanoid motion generation through ZMP manipulation based on inverted pendulum control. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA 2002)*, **2**, May, 1404–1409.

Wickrath, M. 2010. Applied complex motion planning and motion control for humanoid robots in vertical motion sceneries. *Communications in Computer and Information Science* **103**(2), 82–89.

Yi, S.-J., Zhang, B.-T., Hong, D. & Lee, D. D. 2011. Practical bipedal walking control on uneven terrain using surface learning and push recovery. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2011)*, September, 3963–3968.

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