MODELING AND CONTROL OF AUTONOMOUS SKIING ROBOT

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Abstract

This paper presents development of the tools needed for simulation and control of a skiing humanoid robot. The goal of the overall project leads to an autonomous acting robot performing a ski-run based on the carving technique. For the simulation purposes, three main models were developed: model of the robot, model of interaction between skier and environment and the corresponding visualization. Dynamic model of the robot receives information about motion and local inclination from model of environment. Interaction between the skier and an environment consists of the turn of the ski dependent on the edging angle, direction of skiing and calculation of velocity. Information of the robot movement in the environment and the motion of robot itself is sent to the visualization module. Real-time visualization is used for testing of control algorithms for obstacle avoidance and path tracking. We developed also a simplified model of the robot skier for the real-time control. Furthermore, we dealt also with the dynamic stability of the skier based on zero moment point (ZMP). To simplify the calculation algorithm of ZMP on inclined surface we used the Newton-Euler formulation where ZMP is derived directly from the computation of the dynamics equations. Based on ZMP evaluation real-time control of stability for robot is proposed. Finally, simulation on the test course is demonstrated. Two runs are presented. First one has locked torso while second one has a controlled upper-body in order to increase stability. In both cases trajectory of the skier in environment is the same. Increase in lateral stability is shown with proper motion of upper-body.

Keywords: model of skiing robot, interaction between skier and environment, visualization, ZMP stability, simulation

Presenting Author's biography

Leon Lahajnar received his B.Sc. degree in automatics from the University of Ljubljana, Slovenia, in 2003. He is currently PhD Student at the Jozef Stefan Institute, Department for Automatics, Biocybernetics and Robotics. His research area is control of robotic systems based on sensors information similar to human in order to imitate human motion at defined activities.

1 Introduction

Humanoid robots are one of the most challenging research areas in robotics. Researchers are trying to imitate human behavior and tasks with humanoid robots, including sports activities. One of the most popular sport activities is also alpine skiing. There are very few research reported that consider skiing of humanoid robots. In most cases they are limited to perform single action, such as accomplishment of various ski turns. In our project we will integrate most of processes needed for autonomous skiing on the ski slope – autonomous tactic and strategic planning using various sensors and previous experience as well as required motion synthesis which will assure desired path and dynamic stability in the presence of disturbances.

In the last two decades the technique of skiing has changed dramatically due to the carving skis. Previous technique was based on skidding, femur rotation and rotation of the trunk. With introduction of carving skies the skiing has become much easier, because the turns can be achieved only by inclination of skies to the surface.

Before designing a skiing robot, it is necessary to understand the basic mechanisms of skiing. Successful development of such models can have applications in testing of the equipment, teaching and learning of skiing. Yet it must be noted that the motions of a skier are complex, thus requiring effective modeling so as to get to the principles. Some robots were already developed, that were capable to perform turns by performing a predefined set of motion without taking into account the interaction with the environment [2].

Human can perform carving turns in two ways [3]. First possibility is abduction and adduction in the hip. This kind of turn is usually done at low speed. At higher velocity the radial forces in lateral plane are larger. The muscles in the hip are too weak to produce enough force to counteract those lateral forces. Because of that skier at higher speeds execute turn with flexion and extensions of the legs. Stability in the turn is then controlled with upper body.

Our goal is to produce a robot that will be able to ski autonomously at relatively high velocity using carving technique. The skiing robot is composed of two legs and trunk. Leg is build from two parallelograms, which are connected in the way that between the base and the top of a leg there is no rotation. This structure resembles on the moving of a knee and it allows only flexion and extension of the leg. At the base of both legs carving skies are attached. On the top legs are connected to the main body that carries also trunk with ability of leaning left or right. Robot has three actuated joints (one in every knee, and leaning angle of the trunk).

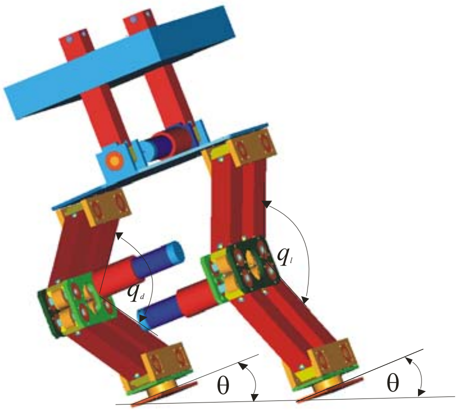

Fig. 1 I-DEAS model of the robot

As it will be showed in continuation proper motion of the upper body can increase stability in transition phase between straight run and turn motion.

2 Modeling of Skiing

Testing of skiing robot, control and tactic algorithms design based solely on experiments is difficult and tedious work, because it has to be accomplished outdoor on the ski slope. Therefore, good and precise simulation tools and environment is required. However, this kind of simulation is very demanding, because it requires precise model of the ski robot, ski surface, terrain and also a realistic visualization of the scene. Visualization is required for the strategic control level, which is based mostly on visual data obtained from the camera. Unfortunately, there is no simulation tool available that will meet all mentioned requirements in real-time. Therefore, the simulation was carried out on three interconnected models. First is a model of the robot, second is model of interaction between the skies and the surface. Last one is visualization of the environment on which robot is moving. Visual information will be used for control of direction of skiing.

2.1 Model of skiing robot

The dynamic model of the robot is used in the simulation of the robot and in the development of the control of the real system. Dynamic model of the robot was built in Matlab SimMechanics [8]. In model we included information about masses, lengths, centers of mass and inertias of robot parts that we acquired from I-DEAS model. Real robot has power supply, control computer, camera and computer for path generation. Mechanical data about those components are also incorporated in the model. According to the data whole weight of the robot will be around 18 kg. Also constraints for maximal torque that motors are able to deliver to actuated joints are included in the model.

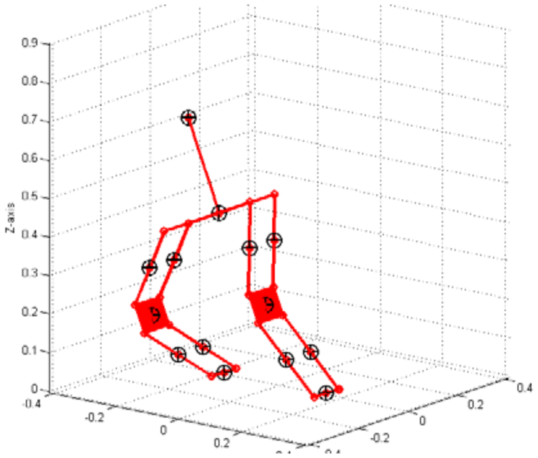

Fig. 2 Model of the skier in SimMechanics

Forces acting on the robot skier can be divided to internal and external forces. Internal forces are caused by the motion of the mechanism itself, while external forces are due to the gravity, radial acceleration and environment. Direction of gravity force depends on inclination of the surface on which robot is at the moment. The size of the radial force acting on skier depends on the turn radius and velocity. Course of the radial force F_r is always parallel to the surface and acts in lateral direction of the skier (Fig. 3).

Fig. 3 Forces acting on the skier in lateral plane.

Radial force equals to:

$$F_r = \frac{m_w v^2}{R}, \qquad (1)$$

where m_w is whole mass of the skier, v is velocity in sagittal plane and R is radius of turn for centre of mass. Distance between the skies changes as one leg is extending and other is flexing, so larger support polygon is established. Stability of the skier can be defined on the dynamic model through the zero moment point (ZMP) [5], which is often used for determining dynamic stability for walking robots and mobile manipulators. It specifies the point on the ground surface there the moments are zero. ZMP should be in our case always between both skies. This can be demonstrated also with the measurement of the ground reaction force in race skiing.

2.2 Model of the interaction between skier and environment

Edging angle θ (Fig 1) of a ski has a pronounced impact on the turn radius. For purely static approach the radius of a carving ski was estimated by Howe [1]:

$$r_{Howe} = \frac{L^2}{8\left[\dfrac{\left(W_S + W_T - 2W_W\right)}{4 \cdot \cos\theta} + d \cdot \sin\theta\right]} \qquad (2)$$

where coefficients L, W_S, W_T, W_W describes geometry of the ski as can be seen on Fig. 4, while d denotes the maximum penetration depth of the ski to the snow, which is dependent on the force acting to the ski, ski stiffness and snow compactness.

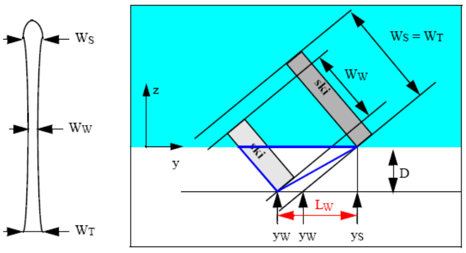

Fig. 4 Presentation of a carving ski inclined to the surface.

Howe radius is defined even for edging angle 0, but real radius for that angle is infinitive. According to the data measured on human skidding it almost disappear for edging angles bigger than 5 degrees. In our model we supposed that in the region of 0 - 5 degrees turn radius is inversely proportional to edging angle.

That radius is calculated for one ski. In our case we supposed that the curvature radius of the turn is between both skis. Also, we supposed that the position of the turn is dependent on forces of skis acting on the surface. If whole force sensed on skis is divided equally, than turn radius curvature is positioned right between them. In other cases position of the turn is located in proportion to forces. Velocity of skier is dependent on angle of inclination of the slope in sagittal plane. Another part that contributes to the decreased velocity is friction and at higher speeds also air resistance. Skiing surface is also included in the model. The data is used for calculation of the local surface inclination and also in visualization.

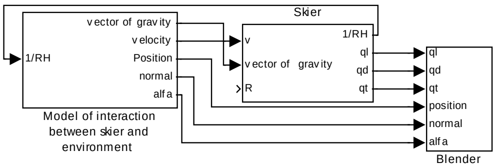

Fig. 5 Combined model in Matlab Simulink

In Fig. 5 structure of whole model is presented. Skier is controlled only with desired turn radius R. The real turn radius that skier execute is dependent on dynamics, constraints and rules that prevents skier to fall. Data of real turn radius are feed to the model of interaction, where velocity data and vector of gravity are calculated and returned to the skier. The set of the data sent to the visualization block comprehends position, orientation, knee and trunk angles of the robot skier respectively.

2.3 Visualization

Visualization of the model is performed in Blender. Blender was basically designed as an environment for the design of arcade games, but has been recently recognized as an efficient tool for the robot simulation in virtual environment. Communication between model in Matlab Simulink and Blender is established through UDP protocol. Data about the skier position, its orientation, and joint angles are in real-time sent to Blender. Mesh of the skiing ground which is used in visualization is also used in the environment model in Simulink.

Fig. 6 Extern view on the skier

Visualization allows us to reconstruct view from the camera (Fig. 7) that is mounted on the top of the trunk. This will enable us to test algorithms for obstacle avoidance and path tracking. According to that information commands for the desired turn radius will be sent back to the model.

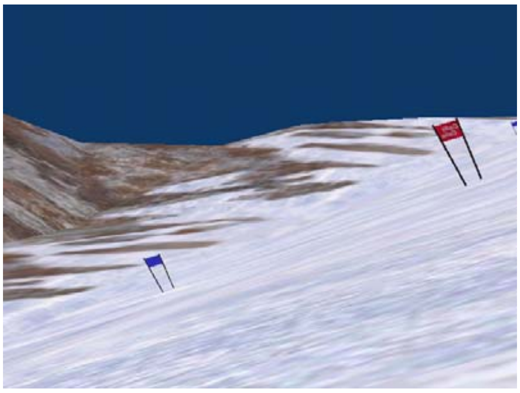

Fig. 7 View from the skier

3 Stability of the skier

Dynamic model that we built in Matlab SimMechanics gave us various information like forces acting to the surface, motor torques needed for actuation. Unfortunately, there is also a disadvantage using SimMechanics in real-time. Due to the complexity of the model, the SimMechanics is not the fastest tool for calculation of dynamics equations [9]. Therefore, we had to simplify the model in order to use it in real-time control. The major problem in skiing is maintaining of stability in lateral direction. On the other hand, the skier is very stable in sagittal plane, where he has support in long skies. In this direction only small forces are acting, which appear mainly due to change in the inclination of the ground and moving of the knee forward. However, in lateral plane larger differences of forces evolves on narrower support plane. Therefore, we will focus only in lateral stability.

3.1 Simplified model of the skier

According to previously mentioned presumptions, the model of the skier in lateral plane can be presented in a following way. Legs in that plane have only one direction of motion so they only make translation in direction of extension of the leg.

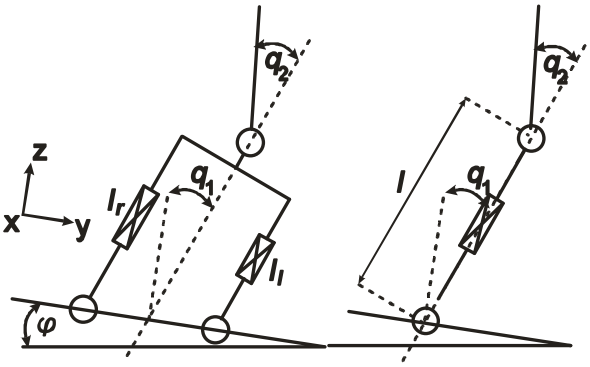

Fig. 8 Simplified model in lateral plane

The edging angle q_1 is the only controllable degree of freedom for our robot that has effect on the direction of moving. We control that angle with extensions (l_r, l_l) of the legs. Value l is a distance between joint that actuate trunk and point on the surface that is right in the middle of both skies. Control will provide that this distance is kept constant. In that case the model of the skier can be represented as a double inverted pendulum.

The most stable position of the skier is when the forces are equally distributed on both skis. In that case ZMP is right in the middle between the legs. When ZMP is outside of the support polygon, one ski will lose the contact with the ground and the skier will fall. In continuation calculation of ZMP for serial mechanism like double inverted pendulum is presented.

3.2 ZMP calculation on inclined surface

Suppose that i-th object has mass m_i at mass centre position r_i with an inertia tensor I_i. External forces and torques are represented with F_k and M_j. The overall rotational and translational equation of the system in arbitrary point P ($p=[x_P\ y_P\ 0]^T$) on plane z=0 equals

$$\begin{aligned}&\sum_i (r_i - p)\times m_i(\ddot{r}_i + g) + \sum_i \left[I_i\omega_i + \omega_i \times I_i\omega_i\right]\\ &-\sum_j M_j - \sum_k (s_k - p)\times F_k = M_P.\end{aligned} \tag{3}$$

Vector s_k points to position where external force F_k acts and g is vector of the gravitational acceleration on an inclined surface and is related to local inclination (φ on Fig. 8) of surface. If we assume that the only external force is radial which works directly in bodies mass centre than Eq. (3) can be rewritten in following way:

$$\begin{aligned}&\sum_i (r_i - p)\times m_i(\ddot{r}_i + g + a_{ri})\\ &+\sum_i \left[I_i\omega_i + \omega_i \times I_i\omega_i\right] = M_P,\end{aligned} \tag{4}$$

where a_{ri} ($a_{ri}=[0\ v^2/R_i\ 0]^T$) is radial acceleration of *i*-th body mass. R_i is the radius of the turn for each body segment. Now, let $T_i = I_i\omega_i + \omega_i \times I_i\omega_i$ because T_i is irrelevant to arbitrary point. That leads to:

$$\sum_i (r_i - p)\times m_i(\ddot{r}_i + g + a_{ri}) + T_i = M_P. \tag{5}$$

According to ZMP definition at point $p_{ZMP} = [x_{ZMP}\ y_{ZMP}\ 0]$ only moment $M_P=[0\ 0\ M_z]^T$ acts. Components of ZMP are

$$\begin{aligned}x_{ZMP} &= \frac{\sum_i m_i(\ddot{z}_i + g_z)x_i - \sum_i m_i(\ddot{x}_i + g_x)z_i}{\sum_i m_i(\ddot{z}_i + g_z)}\\ &-\frac{\sum_i (T_y)_i}{\sum_i m_i(\ddot{z}_i + g_z)}\end{aligned} \tag{6}$$

$$\begin{aligned}y_{ZMP} &= \frac{\sum_i m_i(\ddot{z}_i + g_z)y_i - \sum_i m_i\left(\ddot{y}_i + g_y + \frac{v^2}{R_i}\right)z_i}{\sum_i m_i(\ddot{z}_i + g_z)}\\ &-\frac{\sum_i (T_x)_i}{\sum_i m_i(\ddot{z}_i + g_z)}\end{aligned} \tag{7}$$

Using Newton-Euler formulation for deriving dynamic equations of the system, ZMP can be acquired. An efficient way for the dynamics calculation is recursive Newton-Euler method. First part is forward iteration of the desired joints trajectories. When procedure comes to the last segment of the robot, it starts to calculate forces and moments. For the last segment we get next equations for force and moment acting on previous segment:

$$\begin{aligned}&F_{i-1,i} - m_i(\ddot{r}_i) = 0\\ &M_{i-1,i} + r_{i-1,ci}\times F_{i-1,i} - \left[I_i\dot{\omega}_i + \omega_i \times I_i\omega_i\right] = 0\end{aligned} \tag{9}$$

So we can backward calculate moments and forces for all segments till the first segment where the following equations are obtained:

$$\begin{aligned}&F_{0,1} = F_{1,2} + m_1(\ddot{r}_1 + g + a_{r1}) = \sum_i m_i(\ddot{r}_i + g + a_{ri})\\ &M_{0,1} = M_{1,2} + r_1 \times m_1(\ddot{r}_i + g + a_{r1})\\ &+\left[I_1\dot{\omega}_1 + \omega_1 \times I_1\omega_1\right]\\ &M_{0,1} = \sum_i \left[r_i \times m_i(r_i + g + a_{ri}) + T_i\right]\end{aligned} \tag{10}$$

Eq. (5) can be rewritten in next form

$$\begin{aligned}&M_P = \sum_i \left[r_i \times m_i(\ddot{r}_i + g + a_{ri}) + T_i\right]\\ &-p\times \sum_i m_i(\ddot{r}_i + g + a_{ri})\end{aligned} \tag{11}$$

If we combine equations (10) and (11) we obtain

$$M_P = M_{0,1} - p\times F_{0,1} \tag{12}$$

ZMP point is calculated in following way:

$$x_{ZMP} = \frac{(M_{0,1})_y}{(f_{0,1})_z},\ y_{ZMP} = \frac{(M_{0,1})_x}{(f_{0,1})_z}. \tag{13}$$

In that way ZMP is only by-product of backward iteration of Newton-Euler formulation.

3.3 Control of the skier

Kim [7] presented real-time control of mobile manipulator using potential function for redundant mobile manipulator. Our robot is also redundant because turn radius depends only on inclination of skies to the surface. With proper movement of the upper body skier can be stabilized. This type of improvement can be used for correction short time disturbances, like transition from straight to turn phase when at high speed large radial force appear, but the skier is still in almost upright position. In cases when with torso we can not compensate excessive external forces, we have to use legs in order stabilize the system. In control algorithm we built fuzzy regulator that chooses proper action depending on stability index and current movement of the skier. Stability index is defined as:

$$\boldsymbol{\Phi}(\ddot{q},\dot{q},q,\varphi) = 1 - \left(\frac{y_{MSP} - y_{ZMP}}{b_{sr}(q_1)}\right)^2,$$

(14)

where b_{sr} and y_{MSP} is boundary of stable region in y direction and most stable point, respectively. Stability index is mainly dependent on movement of the legs.

At low radial forces, gravitational forces are dominant. In this case the stability index is below 0,5 and the controller stabilizes the system with the slow torso movement, in order not to produce excessive additional forces due to the torso acceleration. When index is above 0.5 the trunk will move to the zero position and the stability is provided with legs movement only.

4 Simulation results

In the simulation, the robot was placed on the ski slope initial position with non-zero initial velocity. In our model we used skies with sidecut radius of 9 m. Initial velocity is 2 m/s and it increases to around 5 m/s during the ski run. On Fig. 9 track path of the skier is presented.

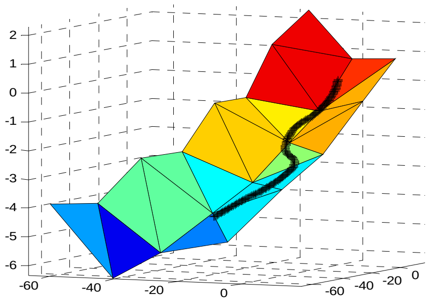

Fig. 9 Track of the skier

Turn radius is controlled real-time in the such a way that robot skis around gates in virtual environment.

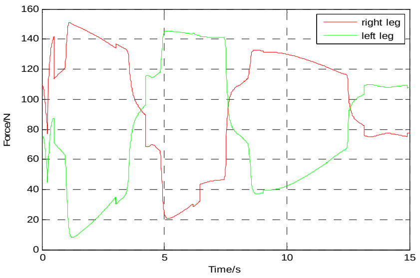

Fig. 10 Forces acting perpendicular to the ski

Fig. 10 shows forces that were acting on the skies. Some picks are visible at the start of the simulation which are caused by contraction of both legs to position where skier can perform turns. It can be seen that during the first two turns outer ski almost lost the contact with the surface. With increased velocity the skier become more stable.

We made also the simulation with the algorithm which enables torso movement. The results are presented in Fig. 11. Edging angle on figure is in degrees divided by 20. ZMP for torso locked in zero position is less stable than when upper body moves according to previously mentioned rules. In both cases performed turns were the same.

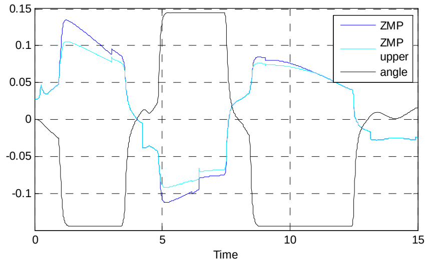

Fig. 11 ZMP with controlled and uncontrolled torso

5 Conclusion

In this article we presented a dynamic model of the skier moving in the virtual environment. Some simplification of the dynamic model of the skier in the lateral plane are introduced to reduce the time required to calculate the dynamics of the robot in real-time. Furthermore, ZMP based on Newton-Euler formulation was proposed. Based on the evaluation of the ZMP, some control strategies for the robot upper-body are proposed. The algorithms were verified with the simulation.

6 References

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