Abstract—This paper proposes a turnover-free control method for a teleoperated mobile agent (or vehicle) moving through uneven terrain. The teleoperated agent is primarily driven by an operator at a remote site and is able to react autonomously when a possible turnover is predicted. In order to predict the turnover, a low-cost terrain prediction sensor has been developed using a camera vision with a structured laser light. Since it is difficult for an operator to predict the reactive motion of the agent, a force reflection technique with a force feedback joystick is employed to intuitively recognize the inconsistency between the intended motion and the reactive motion of the agent. Finally, to verify the feasibility and effectiveness of the proposed method, experiments with the ROBHAZ-DT (actual mobile agent) have been carried out.

Keywords- turnover-free control, terrain prediction, force reflection.
1. **INTRODUCTION**

Teleoperated mobile agents (or vehicles) play an important role especially in hazardous environments such as inspecting underwater structures\(^1\), demining\(^2\) or cleaning nuclear plants\(^3\). A teleoperated agent is, in principle, maneuvered by an operator at a remote site, but should be able to react autonomously to avoid dangerous situations such as collision with obstacles and turnovers. Many studies have been conducted on collision avoidance of mobile agents\(^4,5,6,7,8,9\). In this paper, however, we will focus on turnover prevention of mobile agents moving on uneven terrain because a turnover such as a pitchover or a rollover can fatally damage agents.

Extensive studies related to motion planning problems of mobile agents traveling over sloped terrain have been conducted by the robotics research community. Shiller *et al.* presented optimal motion planning for an autonomous car-like vehicle without a slip and a rollover\(^10\). The terrain was represented by a *B* patch and the vehicle path was represented by a *B* spline curve. Using the models of the terrain and the path, the linear velocity limit of the vehicle to avoid a slip or a rollover was determined. Many studies have been conducted on rollover prevention of heavy vehicles such as trucks and sports utility vehicles by the vehicular research community. In ref. 11, various dynamic outputs of large vehicles such as the lateral acceleration, yaw rate, roll angle and roll rate were analyzed in the frequency domain for predicting rollovers. In ref. 12, the Time-To-Rollover (TTR) based rollover threat index was developed in order to predict rollovers of sports utility vehicles. This intuitive measure, TTR, was computed from the simple model and then corrected by using an artificial neural network. Nalecz *et al.* suggested an energy-based function called the Rollover Prevention Energy Reserve (PRER)\(^13,14,15\). PRER is the difference between the energy needed to bring the vehicle to its rollover position and the rotational kinetic energy, which can be transferred into the gravitational potential energy to lift the vehicle. PRER is
positive for non-rollover cases and negative for rollover cases. Also, in ref. 16, the rollover of commercial vehicles with tanks that are partially filled with liquid cargo was analyzed. In this case, the frequency shaped backstepping sliding mode controller algorithm was designed to stabilize and to attenuate the sloshing effects of the moving cargo by properly choosing the crossover frequencies of the dynamic compensators in accordance with the fundamental frequencies of the slosh dynamics.

Many studies have been conducted on turnover prevention of mobile manipulators such as a fork lift. The scheme for automatic turnover prediction and prevention for a fork lift is described in ref. 17. By monitoring the static and dynamic turnover stability margins of a mobile manipulator, it is possible to predict turnovers and take appropriate actions to prevent a turnover. In this case, the dynamic Force-Angle measure of turnover stability margin proposed by Papadopoulos\textsuperscript{18} is employed. Sugano \textit{et al.} suggested the concepts about stability such as the stability degree and the valid stable region based on the ZMP (Zero Moment Point) criterion to evaluate the stability for a mobile manipulator\textsuperscript{19}. In addition, the method of ZMP path planning by a stability potential field was suggested for recovering and maintaining stability\textsuperscript{20}. Based on the path planning method, the motion of the manipulator is planned in advance to ensure stability while the vehicle is in motion along a given trajectory. Furthermore, for stability recovery, the compensation motion of the manipulator is derived by using the redundancy of the manipulator, taking into consideration the manipulator configuration and the static system stability\textsuperscript{21}.

In the researches related to autonomous mobile agents described above, the path and trajectory of a vehicle and a manipulator were given in advance and modified for turnover prevention. For mobile agents controlled by an operator such as a fork lift, the path and trajectory were estimated by using the proprioceptive sensor data (internal sensor data) for turnover prevention, where it is impossible to know the path and trajectory of the agent in advance since they are determined by
the operator at each time instant. This is also the case for teleoperated agents since the agent is also controlled by an operator at a remote site. However, in the case where there is a potential risk of a turnover due to an abrupt change in the configuration of the ground, the proprioceptive sensor data is not enough to prevent turnovers from occurring. Therefore, in this paper, a low-cost terrain prediction sensor with a camera vision and a structured laser light is proposed for predicting front terrain before the arrival of the agent. With this data, a turnover prevention algorithm is suggested by using the Quasi-static rollover analysis of a rigid vehicle\textsuperscript{22}.

A turnover prevention algorithm includes pitchover and rollover prevention algorithms. According to the turnover prevention algorithm, the linear and rotational velocities of the agent are restricted for avoiding turnovers. However, the turnover prevention control brings about some inconsistencies between the intended motion and the reactive motion of the agent. Thus, a force reflection technique based on virtual reality is employed so that the above-mentioned discrepancy can be recognized. A force reflection technique has already been used in various research areas such as medical surgery\textsuperscript{23,24,25}, micro manipulation\textsuperscript{26,27} and obstacle avoidance of teleoperated mobile agents\textsuperscript{28,29}. In this paper, through force reflection, an operator can make intuitive decisions as to how the agent should be controlled in order to avoid a possible turnover. Here, a 2 DOF (Degree Of Freedom) force feedback joystick is used as a haptic device which not only receives command from an operator but also sends back reflective force to him.

The remainder of this paper will proceed as follows. Section II introduces a teleoperation system and describes basic assumptions for turnover prevention control. In Section III, a low-cost terrain prediction sensor is presented for predicting front terrain. In Section IV, a turnover prevention control algorithm is discussed for avoiding both pitchover and rollover. Section V describes a reflective force generation method for reporting the actual driving states of the controlled agent for turnover prevention. In Section VI, experimental results for verifying the
feasibility and effectiveness of the proposed method are presented with the ROBHAZ-DT (actual mobile agent). Finally, Section VII presents the conclusions.

II. TELEOPERATION SYSTEM AND BASIC ASSUMPTIONS

In this section a teleoperation system which consists of a remote control system (RCS) and a mobile agent system (MAS) is introduced. Basic assumptions for solving a turnover prevention problem are described below.

A. Configuration of the Teleoperation System

A teleoperation system consists of a remote control system (RCS) and a mobile agent system (MAS) as shown in Fig. 1. The RCS and the MAS communicate with each other via wireless Ethernet communication. Control signals and sensor data are denoted in Table I. The RCS receives command from the operator via a force feedback joystick and the joystick positions along the $Y$-axis and the $X$-axis are scaled up or down by the ranges of the linear and rotational velocities of the agent, respectively to control the linear and rotational velocities of the agent. Each of the velocities can be controlled independently since the agent used in this paper is a differential-drive vehicle. In the RCS, a turnover prevention algorithm is implemented with sensor data transmitted from the MAS, and reflective force is generated by the force feedback joystick for reporting the inconsistency between the intended motion and the controlled motion of the agent. In this case, the force feedback joystick is a kind of 2 DOF (Degree Of Freedom) haptic devices.
Fig. 1. Teleoperation system which consists of a RCS and a MAS

Table I. Descriptions of control signals and sensor data

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Descriptions</th>
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<tbody>
<tr>
<td>$F_O(t)$</td>
<td>Input force by the operator command</td>
</tr>
<tr>
<td>$F_R(t)$</td>
<td>Reflective force generated by the force feedback joystick</td>
</tr>
<tr>
<td>$P_J(t)$</td>
<td>Joystick position determined by $F_O(t)$</td>
</tr>
<tr>
<td>$V_{ub,lb}(t)$</td>
<td>Upper and lower bounds of the linear and rotational velocities for avoiding rollover</td>
</tr>
<tr>
<td>$P_{ub,lb}(t)$</td>
<td>Joystick position determined by $V_{ub,lb}(t)$</td>
</tr>
<tr>
<td>$V_{cmd}(t)$</td>
<td>Control command of the agent determined by $P_J(t)$</td>
</tr>
<tr>
<td>$V_d(t)$</td>
<td>Desired velocities for turnover prevention determined by $V_{cmd}(t)$ and $V_{ub,lb}(t)$</td>
</tr>
<tr>
<td>$I_d(t)$</td>
<td>Terrain image data obtained by the camera vision with the structured laser light</td>
</tr>
<tr>
<td>$Tr(t)$</td>
<td>Terrain data obtained after image processing of $I_d(t)$</td>
</tr>
<tr>
<td>$\dot{q}_d(t)$</td>
<td>Desired spinning speed of the actual motors</td>
</tr>
<tr>
<td>$q(t)$</td>
<td>Actual spinning speed of the motors</td>
</tr>
<tr>
<td>$\dot{q}(t)$</td>
<td>Encoder data of the motors</td>
</tr>
</tbody>
</table>

The MAS is composed of a mobile agent and a low-cost terrain prediction sensor. The mobile agent, namely the ROBHAZ-DT, was developed by the Korea Institute of Science and
Technology (KIST). The ROBHAZ-DT has double tracks which allow it to move on uneven terrain. The MAS computes the spinning speeds of two drive wheels from the velocities of the agent transmitted from the RCS and sends them to the embedded controllers that control the actual motors to achieve the desired spinning speeds through internal control loops. A low-cost terrain-prediction sensor consisting of a laser line generator, a web camera and an inclinometer is attached to the ROBHAZ-DT as shown in Fig. 2. The laser line generator, namely the LM-6535ML6D developed by Lanics Co., Ltd., is used to project a line segment on front terrain, and its fan angle and line width are 60º and 1mm, respectively. The wavelength of the laser beam ranges from 645nm to 665nm and the optical output power is 25mW. The CMOS web camera, namely the ZECA MV402 developed by Mtekvision Co., Ltd. is used to detect the line segment projected onto the terrain. The inclinometer, namely the 3DM developed by MicroStrain, Inc., is used to measure the absolute angles from 0º to 360º on both the yaw axis and the pitch axis and from -70º to 70º degrees on the roll axis with respect to the universal frame. The data of the inclinometer are obtained via RS232 Serial interface. The predicted sensor data are eventually sent to the RCS for turnover prevention control.

Fig. 2. Low-cost terrain prediction sensor attached to the ROBHAZ-DT
B. Basic Assumptions

1) The communication period $T_s$ between the RCS and the MAS makes it possible to complete the terrain data acquisition and the motion control of the agent, taking into consideration the maximum time delay for wireless communication. Hereafter, continuous time $t$ shall be discretely described by time index $k$ which denotes time $t = kT_s$.

2) No turnover occurs between the starting position of the agent and the first detected terrain position by the terrain prediction sensor since it is impossible for the agent to avoid turnovers without the terrain sensor data between these two points.

3) The sensor acquisition process for the front terrain is fast enough to obtain the terrain parameters for turnover prevention control. In other words, much more than 2 samples of the front terrain are available for turnover prevention control at each time instant when the agent moves the distance up to its longitudinal length at a normal speed.

4) The agent is represented as one lumped mass located at its center of gravity (CG) since all components of it move together. The point mass at the CG, with appropriate rotational moments of inertia, is dynamically equivalent to the vehicle itself for all motions where it is reasonable to assume that the vehicle is rigid. For acceleration, breaking, and most turning analyses, one mass is sufficient.

5) The agent has a trapezoidal velocity profile. In other words, the linear accelerations for accelerated, uniform and decelerated motions of the agent are determined by constant accelerations $a_c$, 0 and $-a_c$, respectively, where internal controllers of the agent can control the acceleration as the reference $a_c$, 0 or $-a_c$ with tolerable errors. Here, the variation of the acceleration depending on the types of various terrains such as rocky or sandy terrain is not considered. The normal acceleration $a_c$ satisfies the condition $a_c > \frac{v^2}{2D_{tr}}$ where $D_{tr}$ is a
distance to the reference terrain for turnover prevention at each time instant. Thus, the agent can reduce its linear velocity from $v_{\text{max}}$ to zero and stop at worst before it reaches an inevitable turnover terrain at a distance of $D_{tr}$. Here, $D_{tr}$ is determined for the agent to detect the steep slope such as high obstacles which the agent can not go over considering the parameters of the proposed vision system such as the orientations of the camera and the laser light source.

III. FRONT TERRAIN PREDICTION

In this section a terrain prediction sensor is introduced and a terrain data acquisition method is described. Also, the coordinate systems that will be used in the following sections are defined.

A. Vision Data Acquisition for Structured Laser Light

The mobile base frame \{\textit{B}\} of the agent and the camera frame \{\textit{C}\} of the terrain prediction sensor with respect to the universal frame \{\textit{U}\} are depicted in Fig. 3, where the $Y_b$-axis is set parallel with the $Y_c$-axis. The $X_b$-axis of \{\textit{B}\} is parallel with the heading direction of the agent and the $Z_b$-axis is normal to the surface of the ground. The $Y_b$-axis is defined perpendicular to the $X_b$-$Z_b$ plane and its direction is determined by the right-hand-rule (RHR). The origin of \{\textit{B}\} is the agent center position (ACP), which is the projected point of the CG on the $X_b$-$Y_b$ plane. In this paper, all other coordinate systems are also defined in accordance with the RHR. According to the relation between the base and the camera frames, point $P_c(x_c,y_c,z_c) \in \mathbb{R}^3$ relative to \{\textit{C}\} can be transformed into point $P_b(x_b,y_b,z_b) \in \mathbb{R}^3$ relative to \{\textit{B}\} as follows:

$$
\begin{bmatrix}
    x_b \\
    y_b \\
    z_b \\
    1
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta_c & 0 & \sin \theta_c & 0 \\
    0 & 1 & 0 & 0 \\
    -\sin \theta_c & 0 & \cos \theta_c & 1 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    x_c \\
    y_c \\
    z_c \\
    1
\end{bmatrix}
$$

(1)
where \( l_{bc} \) is the distance between origins of \( \{B\} \) and \( \{C\} \), and \( \theta_{bc} \) is the angle between \( \{B\} \) and \( \{C\} \) about the \( Y_b \)-axis.

Fig. 3. Transformation of point \( P_c(x_c, y_c, z_c) \in \mathbb{R}^3 \) relative to \( \{C\} \) into point \( P_b(x_b, y_b, z_b) \in \mathbb{R}^3 \) relative to \( \{B\} \).

In Fig. 4, point \( P_c(x_c, y_c, z_c) \in \mathbb{R}^3 \) on the laser line with respect to \( \{C\} \) is obtained from point \( P_{\text{img}}(u_1, u_2) \in \mathbb{R}^2 \) on the image plane by comparing the similar triangles \( \Delta P_cMC \) and \( \Delta P_{\text{img}}M'C \) as follows:

\[
\begin{bmatrix}
x_c \\
y_c \\
z_c
\end{bmatrix} = \frac{b'}{f \cot \theta_p + u_2} \begin{bmatrix}
f & u_1 & u_2
\end{bmatrix}
\]

where \( f \) is the focal length of the camera, \( \theta_p \) is the projection angle of the laser line on the image plane, and \( b' \) is the distance between the center of the camera lens \( C \) and the intersection \( L' \) of the \( Z_c \)-axis and the laser beam. According to the Sines Law, the distance \( b' \) in triangle \( \Delta LCL' \) can be obtained as follows:

\[
b' = \frac{b \sin(\theta_p - \theta_c)}{\sin(\theta_p)}
\]
where $b$ is the baseline distance between the center of the laser line generator $L$ and the camera center $C$. By (1) and (2), point $P_{\text{img}}(u_1,u_2) \in \mathbb{R}^2$ on the image plane can be transformed into point $P_b(x_b,y_b,z_b) \in \mathbb{R}^3$ relative to $\{B\}$.

![Geometry between point $P_c(x_c,y_c,z_c) \in \mathbb{R}^3$ on the laser line and point $P_{\text{img}}(u_1,u_2) \in \mathbb{R}^2$ on the image plane relative to $\{C\}$](image.png)

**Fig. 4.** Geometry between point $P_c(x_c,y_c,z_c) \in \mathbb{R}^3$ on the laser line and point $P_{\text{img}}(u_1,u_2) \in \mathbb{R}^2$ on the image plane relative to $\{C\}$

**B. Front Terrain Prediction**

The terrain data at a distance of $D_{\text{tr}}$ in front of the agent consist of the roll and pitch angles of the agent set on that terrain. As shown in Fig. 5, the roll angle of the front terrain relative to the current roll angle of the agent is predicted as follows:

$$
\Delta \theta_{\text{roll}}(k) = \tan^{-1}\left(\frac{z_{\text{tr}}(k) - z_{\text{tr}}(k)}{D_{\text{track}}} \right)
$$

(4)

where $D_{\text{track}}$ is a distance between the right and left tracks of the agent. The $P'_{\text{br}}(k)$ and $P'_{\text{bl}}(k)$ are the contact points of the right and left tracks with the front terrain at a distance of $D_{\text{tr}}$, where $P'_{\text{br}}(k)$ and $P'_{\text{bl}}(k)$ are denoted as $(x'_{\text{br}}(k),y'_{\text{br}}(k),z'_{\text{br}}(k))$ and $(x'_{\text{bl}}(k),y'_{\text{bl}}(k),z'_{\text{bl}}(k))$, respectively. The $P'_{\text{br}}(k)$ and $P'_{\text{bl}}(k)$ are obtained as following steps:
1) Store the detected points $P_{br}(k)$ and $P_{bl}(k)$ for the right and left tracks on the laser line and the linear velocity $v(k)$ in the memory at time $k$.

2) For each time instant, find $\Delta k_1$ and $\Delta k_2$ satisfying the following conditions:

\[
\begin{align*}
    x_{bc}(k-\Delta k_1) & \cdot \cos(\theta_{3DM-Pitch}(k-\Delta k_1)) - \sum_{n=1}^{\Delta k_1} v(k-n) \cdot T_s \cdot \cos(\theta_{3DM-Pitch}(k-n)) < D_r \\
    x_{bc}(k-\Delta k_2) & \cdot \cos(\theta_{3DM-Pitch}(k-\Delta k_2)) - \sum_{n=1}^{\Delta k_2} v(k-n) \cdot T_s \cdot \cos(\theta_{3DM-Pitch}(k-n)) < D_r
\end{align*}
\]

where $\theta_{3DM-Pitch}(k)$ is the pitch angle of the agent obtained by the inclinometer at time $k$ relative to the universal frame $\{U\}$.

3) Using $\Delta k_1$ and $\Delta k_2$ satisfying (5) and (6), obtain $P'_{br}(k)$ and $P'_{bl}(k)$ by the linear interpolation of $P_{br}(k-\Delta k_1+1)$ and $P_{br}(k-\Delta k_1)$ and the linear interpolation of $P_{bl}(k-\Delta k_2+1)$ and $P_{bl}(k-\Delta k_2)$, respectively.

Finally, the roll angle relative to the universal frame $\{U\}$ is obtained from the predicted roll angle $\Delta \theta_{Roll}(k)$ relative to $\{B\}$ as follows:

\[
\hat{\theta}_{Roll}(k) = \theta_{3DM-Roll}(k) + \Delta \theta_{Roll}(k)
\]

where $\theta_{3DM-Roll}(k)$ is the roll angle of the agent obtained by the inclinometer at time $k$ relative to $\{U\}$.

![Fig. 5. Predicted roll angle $\Delta \theta_{Pitch}(k)$ at a distance of $D_r$ relative to the roll angle at time $k$ by using interpolated points $P'_{bl}(k)$ and $P'_{br}(k)$ at time $k$](image.png)
As shown in Fig. 6, the pitch angle of the front terrain relative to the current roll angle of the agent is predicted by the terrain data obtained at times \(k\) and \(k - \Delta k_3\) as follows:

\[
\Delta \theta_{\text{Pitch}}(k) = -\tan^{-1}\left(\frac{z'_{\text{bf}}(k) - z'_{\text{bf}}(k - \Delta k_3)}{x'_{\text{bf}}(k) - x'_{\text{bf}}(k - \Delta k_3)}\right) \tag{8}
\]

where \(\Delta k_3\) is the minimum time satisfying the condition \(L_{\text{fr}} \leq |P'_{\text{bf}}(k)P'_{\text{bf}}(k - \Delta k_3)|\). Here, \(L_{\text{fr}}\) is the length of the agent tracks, and \(|P'_{\text{bf}}(k)P'_{\text{bf}}(k - \Delta k_3)|\) is the distance between points \(P'_{\text{bf}}(k)\) and \(P'_{\text{bf}}(k - \Delta k_3)\). Point \(P'_{\text{bf}}(k)\) is defined by points \(P'_{\text{bfL}}(k)\) and \(P'_{\text{bfR}}(k)\) as follows:

\[
P'_{\text{bf}}(k) = (x'_{\text{bf}}(k), y'_{\text{bf}}(k), z'_{\text{bf}}(k)) = \left(D_x, 0, \frac{z'_{\text{bf}}(k) + z'_{\text{bf}}(k)}{2}\right) \tag{9}
\]

To obtain the distance \(|P'_{\text{bf}}(k)P'_{\text{bf}}(k - \Delta k_3)|\), point \(P_{\text{bf}}(k - \Delta k_3)\) relative to base frame \{\(B(k - \Delta k_3)\}\) defined at time \(k - \Delta k_3\) need to be transformed into point \(P'_{\text{bf}}(k - \Delta k_3)\) relative to \{\(B(k)\)\} (or \{\(B\)\}) defined at time \(k\) as follows:

\[
P'_{\text{bf}}(k - \Delta k_3) = P_{\text{bf}}(k - \Delta k_3) - \begin{bmatrix} \sum_{n=1}^{\Delta k_3} v(k - n) \cdot T \cdot \cos(\theta_{\text{SDM-Pitch}}(k - n)) \\ 0 \\ - \sum_{n=1}^{\Delta k_3} v(k - n) \cdot T \cdot \sin(\theta_{\text{SDM-Pitch}}(k - n)) \end{bmatrix} \tag{10}
\]

The second term on the right-hand side of (10) indicates the displacement vector between \{\(B(k - \Delta k_3)\}\) and \{\(B(k)\)\}. Finally, the pitch angle relative to \{\(U\)\} is obtained by the predicted pitch angle \(\Delta \theta_{\text{Pitch}}(k)\) as follows:

\[
\hat{\theta}_{\text{Pitch}}(k) = \theta_{\text{SDM-Pitch}}(k) + \Delta \theta_{\text{Pitch}}(k) \tag{11}
\]
Fig. 6. Predicted pitch angle $\Delta \theta_{\text{Pitch}}(k)$ at a distance of $D_\text{a}$ relative to the pitch angle at time $k$ by using interpolated points $P'_{\text{bf}}(k)$ and $P'_{\text{bf}}(k-\Delta k)$ at time $k$ and $k-\Delta k$, respectively.

IV. TURNOVER PREVENTION THROUGH PREDICTION

In this section a turnover prevention algorithm for preventing the agent from pitching over or rolling over is discussed. The pitchover-free range of the linear acceleration and the rollover-free range of the rotational velocity are determined by using the predicted terrain sensor data. According to the ranges, the linear and rotational velocities of the agent are adjusted to avoid a pitchover or a rollover.

A. Dynamics of the Agent

In order to determine turnover constraints for the agent moving through unknown terrain, we adopt the Quasi-static rollover analysis of a rigid vehicle\textsuperscript{22}. By assuming the ROBHAZ-DT as a rigid vehicle, the deflections of the suspensions and tracks need not be considered in the analysis. The external forces acting on the agent consist of the friction forces between the vehicle and ground, the normal force, and the gravity force. The total friction force $\vec{F}$, tangent to the $X_b-Y_b$ plane, can be defined as follows:

$$\vec{F} = f_{x_v} \vec{X}_b + f_{y_v} \vec{Y}_b$$  \hspace{1cm} (12)
where \( f_{x_i} \) and \( f_{y_i} \) are the components tangent and normal to the heading direction of the agent, respectively. By modifying the dynamic motion equation for the car-like agent described in ref. 10, the equation for a differential-drive agent moving through unknown terrain can be described in terms of the linear velocity \( v \) and the linear acceleration \( a \) as follows:

\[
\begin{align*}
  f_{x_i} \dot{x}_b + f_{y_i} \dot{y}_b + N \dot{z}_b - mg \ddot{z}_u &= \frac{mv^2}{r} \dot{y}_b + ma \dot{x}_b \\
  \end{align*}
\]

where \( N \) is the magnitude of the normal force in the direction of \( \ddot{z}_u \), \( m \) is the lumped mass of the agent, and \( r \) is the turning radius of the agent. Radius \( r \) can be represented as \( v/\omega \) since the agent is a differential-drive vehicle. Parameters \( f_{x_i}, f_{y_i} \) and \( N \) can be obtained by the dot products of the unit vectors \( \ddot{x}_b, \ddot{y}_b \) and \( \ddot{z}_b \) with (13), respectively, as follows:

\[
\begin{align*}
  f_{x_i} &= mg k_{x_i} + ma \\
  f_{y_i} &= mg k_{y_i} + \frac{mv^2}{r} = mg k_{y_i} + m v \omega \\
  N &= mg k_{z_i}
\end{align*}
\]

where \( k_{x_i}, k_{y_i} \) and \( k_{z_i} \) are terrain parameters defined by the projections of unit vector \( \ddot{z}_u \) on unit vectors \( \ddot{x}_b, \ddot{y}_b \) and \( \ddot{z}_b \), respectively. Vector \( \ddot{z}_u \) is the unit vector \([0 \ 0 \ 1]^T\) in the opposite direction of the gravity \([0 \ 0 \ -g]^T\) relative to \( \{U\} \). The terrain parameters are represented by the roll and pitch angles of that terrain as follows:

\[
\begin{align*}
  k_{x_i} &= \ddot{z}_u \cdot \ddot{x}_b = -\sin(\theta_{pitch}) \\
  k_{y_i} &= \ddot{z}_u \cdot \ddot{y}_b = \sin(\theta_{roll}) \cdot \cos(\theta_{pitch}) \\
  k_{z_i} &= \ddot{z}_u \cdot \ddot{z}_b = \cos(\theta_{roll}) \cdot \cos(\theta_{pitch})
\end{align*}
\]

where \( \theta_{roll} \) and \( \theta_{pitch} \) are determined according to the conventional method of the \( X-Y-Z \) fixed angles.
B. Pitchover Prevention Algorithm

The force distribution of the agent is depicted in Fig. 10 (a) and (b) when the agent pitches over CCW and CW about the \( Y_b \)-axis, respectively. At the point where the agent is about to pitch over CCW, the total normal force \( N \) and the friction force \( f_{x_b} \) of the agent are applied on the only front endpoint of the track. Thus, the moment on the agent created by those forces should satisfy the condition \( f_{x_b} h + NL_{p} / 2 \geq 0 \) for preventing a pitchover in a CCW direction; where \( h \) is the height of the CG of the agent. In the same way, the moment on the agent should satisfy the condition \( f_{x_b} h - NL_{p} / 2 \leq 0 \) for preventing a pitchover in a CW direction, where forces \( N \) and \( f_{x_b} \) are applied on the only rear endpoint of the track. Therefore, the resultant condition for preventing a pitchover can be determined by combining the above conditions as follows:

\[
- \frac{NL_{p}}{2h} \leq f_{x_b} \leq \frac{NL_{p}}{2h}
\]  

Substituting (14) and (16) into (20) transforms the resultant condition to an inequality equation in \( a \) as follows:

\[
- g \left( \frac{L_{p}}{2h} k_{z_b} + k_{x_b} \right) \leq a \leq g \left( \frac{L_{p}}{2h} k_{z_b} - k_{x_b} \right)
\]  

Hereafter, the upper and lower bounds of \( a \) in (21) are denoted as \( a_{ub} \) and \( a_{lb} \), respectively. Bounds \( a_{ub} \) and \( a_{lb} \) are represented as surfaces in \( \theta_{Roll}-\theta_{Pitch}-a \) space as shown in Fig. 11, where \( \theta_{Roll} \) and \( \theta_{Pitch} \) replace \( k_{x_b} \) and \( k_{z_b} \) in (21). That is, the inner region between the upper and lower surfaces indicates a safe region of the linear acceleration for preventing a pitchover. In this case, the permitted accelerations of the agent for accelerated, uniform and decelerated motions are represented as three planes \( a=a_{c}, a=0 \) and \( a=-a_{c} \) as shown in Fig. 11.
According to the relation of the two surfaces and the three planes, there are five possible cases of a pitchover as defined in Fig. 12. Each case is determined by the intersection curves of two surfaces with three planes. According to the five cases, the control strategies of the linear velocity for pitchover prevention are described in Table II. For pitchover prevention control, the pitchover possibility is determined by the front terrain data that are predicted by the terrain prediction sensor. When the agent detects the terrain for the absolute pitchover CW or CCW case, the agent
must decelerate to zero because all permitted accelerations of the agent are beyond the boundary of the safe region of the linear acceleration and thus the agent will unconditionally pitch over at the detected terrain. As a result of the deceleration, the agent can stop before arriving at the dangerous terrain. For the potential pitchover CW case, the agent must maintain its velocity or decelerate since it is only allowed to move in a uniform or decelerated motion to avoid the pitchover. Especially, if the agent detects the terrain where it must decelerate in order to prevent from pitching over CW, it will decelerate and stop before it reaches that terrain. That is, the agent does not enter that pitchover region since it already stops at around the vicinity of the region. On the other hand, in the case of the potential pitchover CCW case, the agent must maintain its velocity or accelerate to avoid the pitchover. In this case, the agent can not accelerate any further if its linear velocity has reached the maximum velocity. At this point, the agent must decelerate and stop before it arrives at the terrain. This is similar to the potential pitchover CW case explained above. Finally, in the no pitchover case, the agent is allowed to move in accelerated, uniform and decelerated motions. In other words, the agent need not be controlled for pitchover prevention.

Fig. 12. Five cases for pitchover possibility of the agent according to the roll and pitch angles
Table II. Control strategies of the agent for preventing the pitchover of the agent

<table>
<thead>
<tr>
<th>Cases</th>
<th>Permissible acc. ranges</th>
<th>Possible motions</th>
<th>Control strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Pitchover</td>
<td>$-a_c \leq a \leq a_c$</td>
<td>Accelerated ($a = a_c$)</td>
<td>Needless</td>
</tr>
<tr>
<td></td>
<td>($a_{ub} &gt; a_c$ and $a_{ib} &lt; -a_c$)</td>
<td>Uniform ($a = 0$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decelerated ($a = -a_c$)</td>
<td></td>
</tr>
<tr>
<td>Potential Pitchover CW</td>
<td>$-a_c \leq a \leq 0$</td>
<td>Uniform ($a = 0$)</td>
<td>Maintain the linear velocity of the agent/</td>
</tr>
<tr>
<td></td>
<td>($0 \leq a_{ub} &lt; a_c$ and $a_{ib} &lt; -a_c$)</td>
<td>Decelerated ($a = -a_c$)</td>
<td>Decelerate to zero</td>
</tr>
<tr>
<td></td>
<td>$-a_c \leq a \leq -a_c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>($-a_c \leq a_{ub} &lt; 0$ and $a_{ib} &lt; -a_c$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential Pitchover CCW</td>
<td>$0 \leq a \leq a_c$</td>
<td>Uniform ($a = 0$)</td>
<td>Decelerate to zero</td>
</tr>
<tr>
<td></td>
<td>($a_{ub} &gt; a_c$ and $a_{ib} &lt; a_c$)</td>
<td>Accelerated ($a = a_c$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($a_{ub} &gt; a_c$ and $a_{ib} &lt; 0$)</td>
<td>Accelerated ($a = -a_c$)</td>
<td></td>
</tr>
<tr>
<td>Absolute Pitchover (CCW or CW)</td>
<td>None</td>
<td>None</td>
<td>Decelerate to zero</td>
</tr>
<tr>
<td></td>
<td>($a_{ub} &lt; -a_c$ and $a_{ib} &gt; a_c$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. Rollover Prevention Algorithm

The force distribution of the agent is depicted in Fig. 13 (a) and (b) where the agent rolls over CCW and CW, respectively. In the case where the agent is about to roll over CCW, the total normal force $N$ and the friction force $f_{b_y}$ of the agent are applied on the only left track. Thus, the moment on the agent created by those forces should satisfy the condition $f_{b_y} h + NW_h / 2 \geq 0$ for preventing a rollover in a CCW direction. In the same way, the moment on the agent should satisfy the condition $f_{b_y} h - NW_h / 2 \leq 0$ for preventing a rollover in a CW direction where the forces $N$ and $f_{b_y}$ are applied on only the right track as shown in Fig. 13 (b). Therefore, the resultant condition to prevent a rollover can be determined by combining the above conditions as follows:

$$-NW_h / h \leq f_{b_y} \leq NW_h / h$$

Substituting (15) and (16) into (22) transforms the resultant condition to an inequality equation in $v$ and $\omega$ as follows:

$$-g\left(k_{y_2} + k_{x_2} \frac{W_h / h}{2}\right) \leq v\omega \leq -g\left(k_{y_2} - k_{x_2} \frac{W_h / h}{2}\right)$$

(23)
Hereafter, the upper and lower bounds of $v\omega$ in (23) are denoted as $(v\omega)_{ub}$ and $(v\omega)_{lb}$, respectively. In this case, the linear velocity $v$ is determined by the operator command and the pitchover condition. Thus, for the given $v$, the inequality equation (23) can be represented in terms of $\omega$ as follows:

\[
\frac{(v\omega)_{lb}}{\min(v + \Delta v, v_{max})} \leq \omega \leq \frac{(v\omega)_{ub}}{\min(v + \Delta v, v_{max})}
\]

where $\Delta v$ is the maximum increase of the linear velocity while the agent is moving the distance of $D_{tr}$: $\Delta v = -v + \sqrt{v^2 + 2a \cdot D_{tr}}$. Due to the motor torque constraints, linear velocity $v + \Delta v$ is restricted by $v_{max}$. Here, the upper and lower bounds in (24) are denoted as $\omega_{ub}$ and $\omega_{lb}$, respectively. The rollover-free region of the rotational velocity is defined as the inner region between surfaces $\omega_{ub}$ and $\omega_{lb}$ in $\theta_{Roll}$-$\theta_{Pitch}$-$\omega$ space as shown in Fig. 14. In this figure, three planes $\omega = \omega_{max}$, $\omega = 0$ and $\omega = -\omega_{max}$ for the rotational velocity are also depicted with the surfaces, where $\omega_{max}$ is the maximum rotational velocity of the agent.

![Fig. 13. Force distribution of the agent which is about to roll over (a) CCW and (b) CW](image)

According to the relation of the two surfaces and the three planes, the control regions for rollover prevention are defined as shown in Fig. 15. The boundaries $b_{ui}$ and $b_{lj}$ for $i,j=1,2,3$ are determined by the intersection curves of surfaces $\omega_{ub}$ and $\omega_{lb}$ with the three planes, respectively.
For the free moving region A, the rotational velocity of the agent can be determined for the entire permissible range from $-\omega_{\text{max}}$ to $\omega_{\text{max}}$. That is, the operator can control the agent with no restriction for the rotational velocity. On the contrary, for the restricted regions B1 and B2, the rotational velocity must be restricted for preventing a rollover. If the detected terrain is classified as B1, the rotational velocity is truncated to range from $-\omega_{\text{max}}$ to $\omega_{ub}$ since $\omega_{ub}<\omega_{\text{max}}$. Especially, for the region between $b_{u2}$ and $b_{u3}$, the agent is only allowed to turn right since $\omega_{ub}<0$. In other words, the agent cannot turn left and go straight. For the region B2, the rotational velocity is truncated to range from $\omega_{lb}$ to $\omega_{\text{max}}$ since $-\omega_{\text{max}}<\omega_{lb}$. Similarly to the case of B1, for the region between $b_{l2}$ and $b_{l3}$, the agent is only allowed to turn left since $\omega_{ub}<0$. Finally, if the agent detects any terrain that is classified as the uncontrollable regions C1 and C2, the agent must stop before arriving at that terrain because the whole range from $-\omega_{\text{max}}$ to $\omega_{\text{max}}$ is beyond the safe range from $\omega_{ub}$ to $\omega_{lb}$ and thus the agent will unconditionally roll over at the detected terrain.

![Graphical analysis of the condition for preventing a rollover](image.png)

**Fig. 14.** Graphical analysis of the condition for preventing a rollover ($\omega_{\text{max}}$: maximum rotational velocity of the agent)
Fig. 15. Control regions for rollover prevention according to roll and pitch angles

(A: Free moving region; B1, B2: Restricted regions; C1, C2: Uncontrollable regions)

V. REFLECTIVE FORCE GENERATION

It is possible that turnover prevention control can cause inconsistency between the driving command of the operator and the reactive motion of the agent. Thus, a reflective force is generated to compensate for this inconsistency. The experimental setup for force reflection is depicted in Fig. 16. The WingMan Force Pro joystick of Logitech is employed as a 2 DOF force feedback joystick which not only receives command of an operator but also generates reflective force. The joystick interface is developed by the DirectX 8.0 Software Development Kit (SDK). The positions about the X-axis and the Y-axis of the joystick coordinates determine the rotational and linear velocities of the agent, respectively.
A position-based force $F$ as depicted in Fig. 17 is generated. The force $F$ is determined by the position $q$ about the axis of the joystick coordinates as follows:

$$F = \begin{cases} -k_{NC} \cdot (q - (q_{\text{offset}} - W_{DB})), & q < (q_{\text{offset}} - W_{DB}) \\ -k_{PC} \cdot (q - (q_{\text{offset}} + W_{DB})), & q \geq (q_{\text{offset}} + W_{DB}) \end{cases}$$

(25)

where the parameters of the position-based force are described in Table III. If $q$ is apart from $q_{\text{offset}}$, the reflective force is generated for pushing the joystick to $q_{\text{offset}}$. In other words, the position-based force makes it difficult for the operator to push the joystick far from $q_{\text{offset}}$. In this case, the parameters $F_{PS}$ and $k_{PC}$ for $q > q_{\text{offset}}$ and the parameters $F_{NS}$ and $k_{NC}$ for $q < q_{\text{offset}}$ can be determined independently. In addition, as the dead-band for the reflective force is defined by $W_{DB}$ around $q_{\text{offset}}$, no reflective force is generated if $q$ is located between $(q_{\text{offset}} - W_{DB})$ and $(q_{\text{offset}} + W_{DB})$. Thus, the sensitivity to even a slight movement of $q$ around $q_{\text{offset}}$ can be reduced.
For pitchover prevention, the reflective force about the \( Y \)-axis of the joystick coordinates is generated as shown in Fig. 18 (a). As described in Section IV (b), if the agent detects pitchovers at front terrain, it must keep its linear velocity or decelerate to zero to avoid a pitchover. That is, the desired linear velocity \( v_d \) is set as the current linear velocity of the agent or decreased continuously. Through the reflective force, the operator recognizes that the linear velocity of the agent is restricted by \( v_d \). If the operator pushes the joystick in the positive direction above the joystick position for \( v_d \), he will feel a repulsive force in the negative direction. In contrast, if the operator pulls the joystick in the negative direction below the joystick position for \( v_d \), he will not feel any reflective force. Therefore the operator can guess the upper limit \( v_d \) for pitchover.
prevention by the repulsive force. The parameters of the reflective force are determined as $q_{\text{offset}}=f_1(v_d)$, $W_{\text{DB}}=10^2$, $F_{\text{NS}}=10^4$, $k_{\text{NS}}=0$ and $k_{\text{PS}}=10^4$, where $f_1(\cdot)$ is a mapping function of the desired linear velocity onto the joystick position. In this case, only one parameter $q_{\text{offset}}$ is changed according to the desired linear velocity $v_d$ for pitchover prevention.

For rollover prevention, a reflective force about the $X$-axis is generated as shown in Fig. 18 (b). If the agent detects a possible rollover at the front terrain, the safety range of its rotational velocity is determined to avoid rollovers as was discussed in Section IV (c). The operator can detect the safety range through the reflective force while driving the agent. If the operator maneuvers the agent within this safety range of the rotational velocity, no reflective force is generated. Thus, the operator can drive the agent without any restriction. However, if the operator pushes the joystick out of the safety region, he will feel a reflective force which pushes the joystick in the direction of the safety region. That is, if the operator pushes the joystick above the joystick position for the upper bound of the safety region, the reflective force in the negative direction is generated to prevent from being pushed in the positive direction. Also, in the case where the operator pushes the joystick below the joystick position for the lower bound of the safety region, the reflective force in the positive direction is generated to prevent from being pushed in the negative direction. The parameters $q_{\text{offset}}$ and $W_{\text{DB}}$ of the reflective force about the $X$-axis are determined according to the safe region of the rotational velocity as follows:

$$q_{\text{offset}} = f_2(\omega_{\text{ub}}, \omega_{\text{lb}}) = 10^4 \times \frac{1}{2} \left( \max(\omega_{\text{ub}}, -\omega_{\text{max}}) + \min(\omega_{\text{lb}}, \omega_{\text{max}}) \right)/\omega_{\text{max}}$$

(26)

$$W_{\text{DB}} = f_3(\omega_{\text{ub}}, \omega_{\text{lb}}) = 10^4 \times \frac{1}{2} \left( \min(\omega_{\text{ub}}, \omega_{\text{max}}) - \max(\omega_{\text{lb}}, -\omega_{\text{max}}) \right)/\omega_{\text{max}}$$

(27)

where $f_2(\cdot)$ is a mapping function of the center of the safe region onto the joystick position and $f_3(\cdot)$ is a mapping function of the width of the region onto the dead-band of the reflective force. The other parameters are determined as $F_{\text{NS}}=10^4$, $F_{\text{PS}}=10^4$, $k_{\text{NS}}=10^4$ and $k_{\text{PS}}=10^4$. In this case,
parameters $q_{\text{offset}}$ and $W_{\text{DB}}$ are changed according to the safety region for rollover prevention. Once a reflective force is generated, the operator can intuitively guess how the agent will move to avoid a turnover.

![Reflective forces diagram](image)

Fig. 18. Reflective forces for recognizing (a) the desired linear velocity for pitchover prevention and (b) the safe region of the rotational velocity for rollover prevention

VI. EXPERIMENTAL RESULTS AND DISCUSSION

Two experiments were carried out with the ROBHAZ-DT as an actual mobile agent in order to verify the feasibility of the turnover prevention algorithm suggested in this paper. The sampling time $T_s$ was set as 100 ms, taking into consideration the time delays for sensor acquisition and motion control. Two paths of the agent moving from one starting position to two ending positions are depicted in Fig. 19. The system parameters for these two experiments were set as shown in Table IV.
Fig. 19. Two paths of the ROBHAZ-DT moving from starting position to ending positions on the sloped terrain (Path 1: \( h_1=25 \text{ cm} \), Path 2: \( h_2=70 \text{ cm} \)) where the solid line segment of Path 2 indicates the controlled path for turnover prevention.

Table IV. System parameters for experiments about turnover prevention

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_{\text{max}}=860 )</td>
<td>The maximum linear velocity [( \text{mm/s} )]</td>
</tr>
<tr>
<td>( \omega_{\text{max}}=90 )</td>
<td>The maximum rotational velocity [( \text{deg/s} )]</td>
</tr>
<tr>
<td>( a_c=1500 )</td>
<td>The normal acceleration [( \text{mm/s}^2 )]</td>
</tr>
<tr>
<td>( W_b=48 )</td>
<td>The width between two tracks of the agent [( \text{cm} )]</td>
</tr>
<tr>
<td>( h_1=25, h_2=70 )</td>
<td>The height of the center of gravity of the agent [( \text{cm} )]</td>
</tr>
<tr>
<td>( D_{\text{tr}}=50 )</td>
<td>The reference distance for the turnover prevention [( \text{cm} )]</td>
</tr>
</tbody>
</table>

The first experiment was carried out with only a mobile base of the ROBHAZ-DT, where \( h_1=25 \text{ cm} \). The agent moved along path 1 for 6.7 seconds as shown in Fig. 19. The terrain parameters at a distance of \( D_{\text{tr}} \) in front of the agent are depicted in Fig. 20 (a). These parameters were predicted by the terrain prediction sensor and used for turnover prevention. In this experiment, no turnover was detected in the front terrain and thus the linear and rotational velocities of the agent need not be controlled for turnover prevention. That is, the desired linear velocity \( v_d \) for pitchover prevention was set as the maximum linear velocity \( v_{\text{max}} \) of the agent and the safety region of the rotational velocity covered the whole range of the rotational velocity of...
the agent as shown in Fig. 20 (b). Also, reflective force for turnover prevention was not generated and thus the operator could control the agent freely as shown in Fig. 20 (c) and (d).

![Graphs showing experimental results](image)

Fig. 20. Experimental results about turnover prevention ($W_b=48 \text{ cm}$ and $h_1=25 \text{ cm}$): (a) terrain parameters at a distance of $D_{tr}$ in front of the agent; (b) rotational and linear velocities; (c) joystick parameters about the $Y$-axis; and (d) joystick parameters about the $X$-axis.

The second experiment was carried out using the mobile base with a manipulator. In this experiment, we assumed that the configuration of the manipulator was fixed while the agent was in motion since the action of the manipulator might bring about change of the center of gravity (CG) of the agent. In this case, although the CG of the agent was not changed, the height $h_1$ of the CG rose up to 70 cm due to the mass of the manipulator attached to the mobile base. In the second experiment, the agent moved along path 2 for 6.3 seconds as shown in Fig. 19. The solid
line segment of Path 2 in Fig. 19 indicates that the agent was controlled for turnover prevention. If the agent moves in the turnover segment without controllers, the agent is easily turned over depending on the operator command.

The terrain parameters at a distance of $D_t$ in front of the agent are depicted in Fig. 21 (a). In this case, the agent detected turnovers in the front terrain and thus the linear and rotational velocities of the agent were controlled as shown in Fig. 21 (b). For the given terrain parameters at each time instant, the desired linear velocity $v_d$ was controlled and the linear velocity $v_{cmd}$ of the operator command was restricted by $v_d$ for pitchover prevention. As shown in Fig. 21 (b), the resultant linear velocity $v$ is decelerated and accelerated by $-a_c$ and $a_c$, respectively, to follow the desired velocity $v_d$. Also, the upper bound of the safety region of the rotational velocity was determined for rollover prevention and the rotational velocity $\omega_{cmd}$ of the operator command was restricted by this safety region. As shown in Fig. 21 (c), when the joystick position for $v_{cmd}$ exceeded $v_d$, the reflective force about the Y-axis was generated in the negative direction. As a result, the operator felt a repulsive force preventing him from being pushed, and hence recognized that the linear velocity of the agent was restricted by $v_d$ for pitchover prevention. Also, when the joystick position for $\omega_{cmd}$ exceeded the upper bound of the safe region, the reflective force about the X-axis was generated in the negative direction and vice versa. Thus, through the reflective force, the operator could intuitively recognize the safe region of the rotational velocity for rollover prevention and thus be guided to control the rotational velocity within the safety range.
VII. CONCLUSION

The algorithm for turnover prevention of a teleoperated mobile agent was presented. For online prediction of front terrain, a low-cost terrain prediction sensor composed of a camera vision, a laser line generator and an inclinometer was developed. The terrain parameters were obtained by finding structured laser line projected onto the front terrain and used for turnover prevention control through the Quasi-static rollover analysis. As a result of turnover prevention control, the linear and rotational velocities of the agent were restricted. However, the velocity restriction for
turnover prevention may bring about the inconsistency between the intended motion and the controlled motion of the agent. Thus, the force reflection technique was employed in order to compensate the operator for the motion inconsistency. Through the position-based reflective force, the operator could intuitively recognize how the agent should be controlled to avoid turnovers. Finally, based on the experimental results, we found that the agent can even avoid turnovers in unknown sloped terrain. In further works, we will extend the proposed turnover prevention control algorithm to mobile manipulators whose center of mass can change during motion of its mobile base and investigate a slip prevention control algorithm for track-type mobile agents.

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IX. REFERENCES


