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Vision-based External Force Estimation for Mobile Robots

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Abstract: This paper describes an approach of vision-based external force estimation for mobile robots. The force related motion control such as force control, compliant control, impedance control and so on, requires the force sensing property. And the visual information is one of important resources for recognizing environments in mobile systems. In the proposed approach, external force and robot velocity are estimated only from visual information. Therefore, any internal sensors, such as force/torque sensor, encoder and tachometer, are not required for force sensing. The robot motion is estimated from optical flow field and disparity vector by stereo vision system, furthermore external force can be calculated by reaction force observer. The vision-based approach has a remarkable potential function, that is virtual external force affected by remote object motion in visual scene, can be generated intentionally. The validity of the proposed approach is verified by several experimental results.

1. INTRODUCTION

For human-friendly robots, the force related motion control is one of important issues. For example, the impedance control is useful for compliant interactions between external force and robot motion. Such interactions between robots, human and contacting environments are indispensable property especially in human assistive devices. On the other hand, the environmental information of the robot workspace is essential resources for robot mobility under autonomous navigation. The vision-guided motion control is one of solutions for mobile robots to move and work properly under various environments.

This paper describes an approach of vision-based external force estimation for mobile robots. In this approach, both of external force and robot motion are estimated only from visual information. Generally, the force related motion control such as force control, compliant control, impedance control and so on, requires the force sensing property. The sensor-based approach has a limitation that the external force needs to be affected in the part of sensor area. In the proposed method, any internal sensors, such as force/torque sensor, encoder and tachometer, are not required for sensing external force. The robot motion is estimated from optical flow field and disparity vector by stereo vision system, and then external force can be calculated by reaction force observer.

In the past researches, the sensor-less approach for external force observation have been proposed for manipulators, robotic wheelchair and so on (see references [1], [2], [3]). The observer-based approach using internal model is one of powerful techniques for robot systems. Generally the fast and accurate motion signals, such as from encoder signal or tachometer etc., are required for real-time estimation. In the meantime, recent computing technologies are developed remarkably, and real-time performance is increasing for vision-based processing and recognition. Therefore the authors have been tried to integrate the force sensing and vision-based recognition ([9]). Our approach employs vision-based motion estimation in which the robot velocity is estimated by using disparity vectors(DV) and optical flow vectors(OFV) from stereo images in real-time. The vision-based motion control and motion estimation including object detections are well described in several references ([4, 5, 6]). The DV and OFV are calculated by block matching algorithm from right/left images and two consecutive ones respectively. The estimated motion signal is used in the reaction force observer. Furthermore, the vision-based approach has a remarkable potential function that virtual external force affected by remote object motion in visual scene can be generated intentionally. The paper describes an example modeling and discussions with the effects of virtual remote force.

The remainder of this paper is organized as follows. In Section 2, the targeting robot model is presented. In Section 3, the image processing for velocity estimation is presented. The vision based reaction force observer and its features are discussed in Section 4. The proposed method is verified by several experimental results in Section 5. Conclusions and future work are described in Section 6.

2. ROBOT MODELING

2.1 Kinematics

Target mobile robot model, which is differential-drive type, is shown in Fig.1. Several parameters are listed as follows:

θ_l, θ_r	: Angle of left/right wheel
θ	$= [\theta_l,\ \theta_r]^T$:Vector Formulation
R	: Wheel Radius
W	: Wheelbase
v	: Translational Velocity
ω	: Rotational Velocity
$\boldsymbol{v}_r$	$= [v,\ \omega]^T$:Robot Velocity Vector
$\boldsymbol{r}_c$	: Camera Position Vector in Robot Frame

Then the robot velocity vector can be represented in matrix-vector form (1).

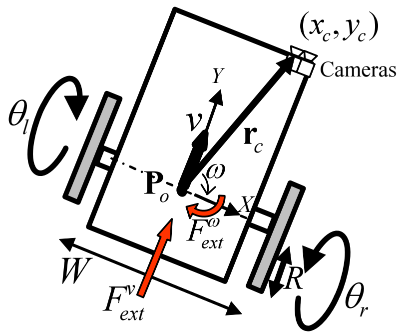


Fig. 1. Target Robot Model

$$\boldsymbol{v}_r = \begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{R}{2} & \frac{R}{2} \\ \frac{R}{W} & -\frac{R}{W} \end{bmatrix} \begin{bmatrix} \dot{\theta}_r \\ \dot{\theta}_l \end{bmatrix} = \boldsymbol{T}\dot{\theta} \tag{1}$$

where $\boldsymbol{T}$ is transformation matrix from wheel space to robot motion space. The acceleration relation is also given by time derivative of (1).

$$\dot{\boldsymbol{v}}_r = \boldsymbol{T}\ddot{\theta} \tag{2}$$

2.2 Dynamics

The dynamics equation in wheel space can be written in following formulation. (See [7])

$$\boldsymbol{M}_w\ddot{\theta} = \boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{T}_{dis} - \boldsymbol{T}_{ext} \tag{3}$$

where

$$\boldsymbol{M}_w = \begin{bmatrix} \frac{MR^2}{4} + J_w + \frac{JR^2}{W^2} & \frac{MR^2}{4} - \frac{JR^2}{W^2} \\ \frac{MR^2}{4} - \frac{JR^2}{W^2} & \frac{MR^2}{4} + J_w + \frac{JR^2}{W^2} \end{bmatrix} \tag{4}$$

Several parameters are listed as follows:

M : Mass of Robot
J : Inertia of Robot around $\boldsymbol{P}_o$
J_w : Inertia of a Wheel
$\boldsymbol{K}_{tn}$: Torque Coefficient of Motors(diagonal matrix)
$\boldsymbol{I}_a$: Armature Current Vector
$\boldsymbol{T}_{dis}$: Disturbance Torque Vector including Frictions
$\boldsymbol{T}_{ext}$: External Torque Vector

The wheel acceleration can be obtained from (3).

$$\ddot{\theta} = \boldsymbol{M}_w^{-1}(\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{T}_{dis} - \boldsymbol{T}_{ext}) \tag{5}$$

And the external force $\boldsymbol{F}_{ext} = [F_{ext}^v \;\; F_{ext}^\omega]^T$ described in robot frame can be translated into wheel space as follows:

$$\boldsymbol{T}_{ext} = \boldsymbol{T}^T\boldsymbol{F}_{ext} \tag{6}$$

By substituting equations (5) and (6) into (2) and rearranging, the motion equation in robot space can be represented as (7).

$$\boldsymbol{M}_r\dot{\boldsymbol{v}}_r = \boldsymbol{T}^{-T}\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{T}^{-T}\boldsymbol{T}_{dis} - \boldsymbol{F}_{ext} \tag{7}$$

where

$$\boldsymbol{M}_r = (\boldsymbol{T}\boldsymbol{M}_w^{-1}\boldsymbol{T}^T)^{-1} = \begin{bmatrix} M + \frac{2J_w}{R^2} & 0 \\ 0 & J + \frac{W^2J_w}{2R^2} \end{bmatrix} \tag{8}$$

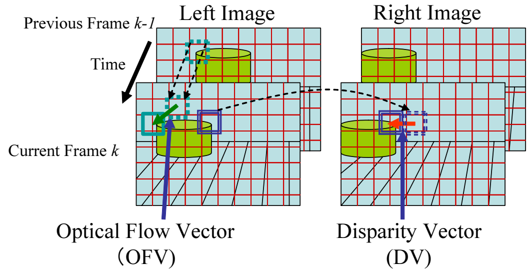


Fig. 2. Optical Flow Vector and Disparity of Stereo Images

3. VISION-BASED MOTION ESTIMATION

By using stereo cameras mounted on the mobile robot, these images can be used for robot motion estimation. Each image is divided to small cell blocks as shown in Fig.2, and DV between left and right images, and OFV in consecutive left images are calculated respectively by normalized correlation matching algorithm.

3.1 Analysis of Optical Flow Field

The horizontal disparity d_i yields the z-axis position Z_i of corresponding block area by (9).

$$Z_i = \frac{L}{d_i}f \tag{9}$$

where L and f are the interval of stereo cameras and focal length respectively. Subscript i means the block number.

In Fig.3, the camera coordinate and several parameters are specified. Assuming that the target viewing point $\boldsymbol{P}_i = (X_i, Y_i, Z_i)$ is stationary in world coordinate, the relation between camera motion and $\boldsymbol{P}_i$ in camera frame can be written as (10).

$$\dot{\boldsymbol{P}}_i = \frac{d\boldsymbol{P}_i}{dt} = -(\boldsymbol{V} + \Omega \times \boldsymbol{P}_i) \tag{10}$$

where $\boldsymbol{V}$ and Ω are translational camera velocity $[V_x, V_y, V_z]^T$ and rotational velocity $[\omega_x, \omega_y, \omega_z]^T$ respectively. When the point $\boldsymbol{P}_i$ is projected onto the image plane at $\boldsymbol{p}_i = (x_i, y_i)$, the relation between $\boldsymbol{P}_i$ and $\boldsymbol{p}_i$ is given by (11).

$$x_i = \frac{fX_i}{Z_i}, \quad y_i = \frac{fY_i}{Z_i} \tag{11}$$

The time derivative of (11) can be calculated as follows:

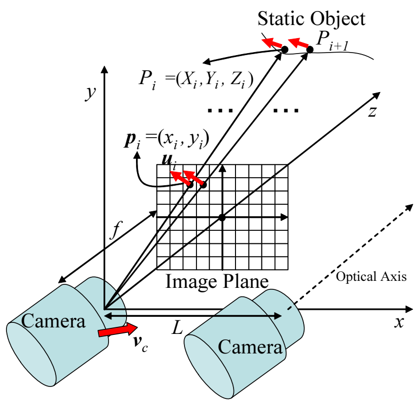


Fig. 3. Definition of Sensor and Image Coordinates

$$u_i = \frac{dx_i}{dt} = \frac{1}{Z_i}(f\frac{dX_i}{dt} - x_i\frac{dZ_i}{dt}) \tag{12}$$

$$v_i = \frac{dy_i}{dt} = \frac{1}{Z_i}(f\frac{dY_i}{dt} - y_i\frac{dZ_i}{dt}) \tag{13}$$

The vector $\boldsymbol{u}_i = [u_i, v_i]^T \in \mathbb{R}^2$ is an optical flow vector at $\boldsymbol{p}_i$. By substituting (10) into (12) and (13), the final formulation is obtained as (14).

$$\boldsymbol{u}_i = \begin{bmatrix} u_i \\ v_i \end{bmatrix} = \frac{1}{Z_i}\begin{bmatrix} -f & 0 & x_i \\ 0 & -f & y_i \end{bmatrix}\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} + \frac{1}{f}\begin{bmatrix} x_i y_i & -f^2 - x_i^2 & f y_i \\ f^2 + y_i^2 & -x_i y_i & -f x_i \end{bmatrix}\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{14}$$

Equation (14) can be simply rewritten in vector and matrix form as (15).

$$\boldsymbol{u}_i = \boldsymbol{J}_{img}(x_i, y_i, Z_i)\boldsymbol{v}_c \tag{15}$$

where $\boldsymbol{v}_c = [V_x, V_y, V_z, \omega_x, \omega_y, \omega_z]^T$, and $\boldsymbol{J}_{img} \in \mathbb{R}^{2\times 6}$ is so-called image Jacobian matrix.

3.2 Robot Velocity Estimation

The velocity relation between the robot and camera frames can be represented in following form.

$$\boldsymbol{v}_c = \boldsymbol{H}(\boldsymbol{r}_c)\boldsymbol{v}_r \tag{16}$$

where $\boldsymbol{r}_c \in \mathbb{R}^2$ is camera position vector in robot coordinate as shown in Fig.1, and $\boldsymbol{H} \in \mathbb{R}^{6\times 2}$ means transformation matrix for relating the robot motion vector to camera frame. Here the floor is assumed to be horizontal and flat. By substituting (16) into (15), the relation between OFV and robot velocity can be rearranged as shown in the following formulation.

$$\begin{aligned} \boldsymbol{u}_i &= \boldsymbol{J}_{img}(x_i, y_i, Z_i)\boldsymbol{H}(\boldsymbol{r}_c)\boldsymbol{v}_r \\ &= \boldsymbol{J}'_{img}(x_i, y_i, Z_i)\ \boldsymbol{v}_r \end{aligned} \tag{17}$$

Here $\boldsymbol{J}'_{img}$ is given as 2×2 matrix. For obtaining the robot velocity, a linear least squares problem is solved by using all OFVs of whole image area as follows:

$$\begin{bmatrix} \boldsymbol{u}_1 \\ \vdots \\ \boldsymbol{u}_i \\ \vdots \\ \boldsymbol{u}_n \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}'_{img}(x_1, y_1, Z_1) \\ \vdots \\ \boldsymbol{J}'_{img}(x_i, y_i, Z_i) \\ \vdots \\ \boldsymbol{J}'_{img}(x_n, y_n, Z_n) \end{bmatrix} \boldsymbol{v}_r = \boldsymbol{J}_{all}\ \boldsymbol{v}_r \tag{18}$$

where the subscript n means the total number of blocks. The solution can be given as (19).

$$\hat{\boldsymbol{v}}_r = (\boldsymbol{J}_{all}^T \boldsymbol{W} \boldsymbol{J}_{all})^{-1} \boldsymbol{J}_{all}^T \boldsymbol{W} \begin{bmatrix} \boldsymbol{u}_1 \\ \vdots \\ \boldsymbol{u}_n \end{bmatrix} \tag{19}$$

In this equation, $[\boldsymbol{u}_1, \cdots, \boldsymbol{u}_n]^T$ are OFVs obtained by block matching algorithm as shown in Fig.2. The matrix $\boldsymbol{W} \in \mathbb{R}^{2n\times 2n}$ means the weighting factors for choosing each weight of the OFV.

$$\boldsymbol{W} = diag(\boldsymbol{w}_{u_1}^T, \cdots \boldsymbol{w}_{u_i}^T, \cdots \boldsymbol{w}_{u_n}^T) \tag{20}$$

where $\boldsymbol{w}_{u_i}$=$[w_{u_i},\ w_{v_i}]^T$. Here w_{u_i}, w_{v_i} are scalar values for weighting each OFV element in image plane. These values are determined according to the dynamic block area detection as shown in next subsection.

3.3 Dynamic Object Block Detection

If some dynamic objects exist in the field of view, there is possibility that the estimated velocity (19) is influenced from the motion of dynamic objects.

Assuming that environment is static, then the ideal OFV field can be obtained by using current estimated velocity.

$$\boldsymbol{u}_i^{ideal} = \boldsymbol{J}'_{img}(x_i, y_i, Z_i)\hat{\boldsymbol{v}}_r \tag{21}$$

The difference index between actual OFV and ideal one can be simply defined as following.

$$\alpha = ||\boldsymbol{u}_i - \boldsymbol{u}_i^{ideal}||_2 \tag{22}$$

where $||\cdot||_2$ means Euclid norm. In case the index α becomes large value, the cell block in the image may correspond to the dynamic object area. In order to reject such OFV for robot motion estimation, the weighting values are determined by using threshold value t as following manner.

$$\boldsymbol{w}_{u_i} = \begin{bmatrix} w_{u_i} \\ w_{v_i} \end{bmatrix} = \begin{cases} [0,0]^T & (\alpha \geq t) \\ [1,1]^T & (\alpha < t) \end{cases} \tag{23}$$

The intermediate value $0 \sim 1$ of weighting factors has remarkable meaning in vision-based approach, and it is analyzed in subsection 4.2.

4. REACTION FORCE OBSERVER

4.1 Reaction Force Observer

In observer-based approach, the external force is estimated as reaction force generated by robot actuators. In this case, the robust motion controller in acceleration dimension is expected for obtaining the effective reaction force. Therefore the disturbance observer is applied as each wheel acceleration controller, and the block diagram is shown in Fig.4. The observer estimates the sum of $\boldsymbol{T}_{dis}$ and $\boldsymbol{T}_{ext}$ in (3) and these disturbances including external torque can be compensated by additional current $\boldsymbol{I}_{cmp}$ (see [8]). Therefore the wheel motion can be described as nominal model in disturbance observer-based system.

$$\boldsymbol{M}_w^{nom}\ddot{\theta} = \boldsymbol{K}_{tn}\boldsymbol{I}_a^{ref} \tag{24}$$

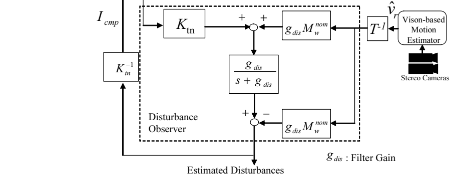


Fig. 4. Disturbance Observer-based Acceleration Controller

where $\boldsymbol{M}_w^{nom}$ means nominal inertia matrix. Then the motion equation in robot space is also represented as (25) from (7). Because the sum of $\boldsymbol{T}_{dis}$ and $\boldsymbol{T}_{ext}$ is already compensated by the current $\boldsymbol{I}_{cmp}$ in Fig.4.

$$\boldsymbol{M}_r\dot{\boldsymbol{v}}_r = \boldsymbol{T}^{-T}\boldsymbol{K}_{tn}\boldsymbol{I}_a^{ref} \tag{25}$$

Therefore the current reference for desired acceleration $\dot{\boldsymbol{v}}_r$ can be given as following formulation.

$$\begin{aligned}\boldsymbol{I}_a^{ref} &= \boldsymbol{K}_{tn}^{-1}\boldsymbol{T}^T\boldsymbol{M}_r\dot{\boldsymbol{v}}_r \\ &= \boldsymbol{K}_{tn}^{-1}\boldsymbol{M}_w^{nom}\boldsymbol{T}^{-1}\dot{\boldsymbol{v}}_r\end{aligned} \tag{26}$$

The total of generating motor torque τ (=$\boldsymbol{K}_{tn}\boldsymbol{I}_a$) is calculated by considering the current $\boldsymbol{I}_{cmp}$.

$$\tau = \boldsymbol{K}_{tn}\boldsymbol{I}_a = \boldsymbol{K}_{tn}(\boldsymbol{I}_a^{ref} + \boldsymbol{I}_{cmp}) \tag{27}$$

The motor torque $\boldsymbol{K}_{tn}\boldsymbol{I}_a$ includes the reaction torque corresponding to the external force $\boldsymbol{F}_{ext}$. Finally the reaction force $\boldsymbol{F}_{reac}$ can be obtained analytically as shown in (28) by subtracting disturbances and motion force from total force in robot space.

$$\boldsymbol{F}_{reac} = \boldsymbol{T}^{-T}\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{T}^{-T}\boldsymbol{T}_{dis} - \boldsymbol{M}_r\dot{\boldsymbol{v}}_r \tag{28}$$

The disturbance is regarded as the frictions which include coulomb friction $\boldsymbol{F}_c$ and viscosity one $\boldsymbol{D}\dot{\boldsymbol{\theta}}$. These parameters are identified through several motion tests in advance.

$$\boldsymbol{T}_{dis} = \boldsymbol{F}_c + \boldsymbol{D}\boldsymbol{T}^{-1}\hat{\boldsymbol{v}}_r \tag{29}$$

From (28), the reaction force observer can be designed by using the estimated velocity $\hat{\boldsymbol{v}}_r$.

$$\begin{aligned}\hat{\boldsymbol{F}}_{reac} &= \frac{g_{est}}{s+g_{est}}\{\boldsymbol{T}^{-T}(\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{F}_c - \boldsymbol{D}\boldsymbol{T}^{-1}\hat{\boldsymbol{v}}_r) - s\boldsymbol{M}_r\hat{\boldsymbol{v}}_r\} \\ &= \frac{g_{est}}{s+g_{est}}\{\boldsymbol{T}^{-T}(\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{F}_c - \boldsymbol{D}\boldsymbol{T}^{-1}\hat{\boldsymbol{v}}_r) \\ &\qquad + g_{est}\boldsymbol{M}_r\hat{\boldsymbol{v}}_r\} - g_{est}\boldsymbol{M}_r\hat{\boldsymbol{v}}_r\end{aligned} \tag{30}$$

In this equation, the 1st order low pass filter with gain g_{est} is inserted for removing noise effects in the differentiation of $\hat{\boldsymbol{v}}_r$. Final block diagram of this observer is shown in Fig.5.

4.2 Virtual External Force from Dynamic Environments

It is expected that the estimated force in (30) becomes actual reaction one when $\hat{\boldsymbol{v}}_r$ is almost equal to real velocity of mobile robot. However the vision-based motion estimation described in Section.3 has flexibilities for reflecting the environmental information, such as dynamic object motion. Equation (23) means one of selections for completely removing the effects of the dynamic environments.

For example, the weighting factors for each block can be given as following manner.

$$\boldsymbol{w}_{u_i} = \begin{bmatrix} w_{u_i} \\ w_{v_i}\end{bmatrix} = \begin{cases}[w_{obj}, w_{obj}]^T & (\alpha \geq t) \\ [1,1]^T & (\alpha < t)\end{cases} \tag{31}$$

where w_{obj} sets to $0 < w_{obj} \leq 1$. In this case, the estimated velocity $\hat{\boldsymbol{v}}_r$ includes the motion influences of dynamic object. Here the new velocity $\hat{\boldsymbol{v}}_r^{dyn}$ estimated by using (31) is defined distinctively, and is used intentionally in the part of reaction force observer (30). That is, the equation is rewritten.

$$\begin{aligned}\hat{\boldsymbol{F}}_{reac} = \frac{g_{est}}{s+g_{est}}\{&\boldsymbol{T}^{-T}(\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{F}_c - \boldsymbol{D}\boldsymbol{T}^{-1}\hat{\boldsymbol{v}}_r) \\ &+ g_{est}\boldsymbol{M}_r\hat{\boldsymbol{v}}_r^{dyn}\} - g_{est}\boldsymbol{M}_r\hat{\boldsymbol{v}}_r^{dyn}\end{aligned} \tag{32}$$

Analytically the estimated force is expected to be next formulation from (28).

$$\boldsymbol{F}_{reac} = \boldsymbol{T}^{-T}\boldsymbol{K}_{tn}\boldsymbol{I}_a - \boldsymbol{T}^{-T}\boldsymbol{T}_{dis} - \boldsymbol{M}_r\dot{\hat{\boldsymbol{v}}}_r^{dyn} \tag{33}$$

The actual effects of using (32) in the force estimation is discussed in the followings. For simplicity, one object is assumed to be in the field of view, and it has only translational velocity in world coordinate. These assumptions can be seen in Fig.6. Under this condition, the detected OFV $\boldsymbol{u}_i$ will be given as (34) theoretically.

$$\boldsymbol{u}_i = \boldsymbol{J}'_{img}(x_i, y_i, Z_i)\boldsymbol{v}_r - s_i\boldsymbol{J}_{img}^{ZX}(x_i, y_i, Z_i)\boldsymbol{v}_{obj} \tag{34}$$

Here $\boldsymbol{v}_{obj}$ means the object absolute velocity in world coordinate Σ^W as shown in Fig.6. At this time, the robot pose is assumed to be directed to x-axis of Σ^W. And s_i is defined as scalar switch value. In case that i-th block in the image corresponds to a dynamic object area, $s_i = 1$, otherwise $s_i = 0$. $\boldsymbol{J}_{img}^{ZX} \in \mathbb{R}^{2\times 2}$ means the interaction matrix between camera and object. It is obtained from the part of (14) involving the translational velocity of Z and X axis in camera frame.

$$\boldsymbol{J}_{img}^{ZX} = \frac{1}{Z_i}\begin{bmatrix} x_i & -f \\ y_i & 0\end{bmatrix} \tag{35}$$

By using these OFVs described in (34), the estimated velocity obtained from (19) can be represented theoretically.

$$\begin{aligned}\hat{\boldsymbol{v}}_r^{dyn} &= (\boldsymbol{J}_{all}^T\boldsymbol{W}\boldsymbol{J}_{all})^{-1}\boldsymbol{J}_{all}^T\boldsymbol{W}(\boldsymbol{J}_{all}\boldsymbol{v}_r - \boldsymbol{S}\boldsymbol{J}_{all}^{ZX}\boldsymbol{v}_{obj}) \\ &= \boldsymbol{v}_r - \boldsymbol{R}\boldsymbol{v}_{obj}\end{aligned} \tag{36}$$

where

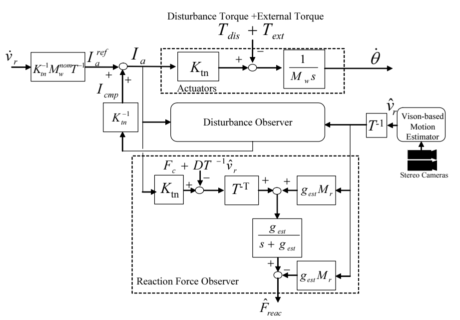


Fig. 5. Reaction Force Observer

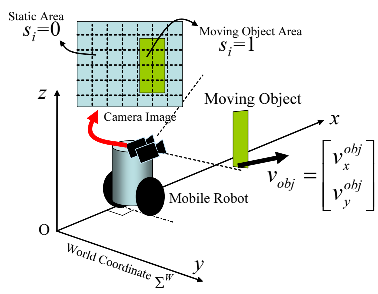


Fig. 6. Moving Object Definition

$$\boldsymbol{R} = (\boldsymbol{J}_{all}^T \boldsymbol{W} \boldsymbol{J}_{all})^{-1} \cdot (\boldsymbol{J}_{all}^T \boldsymbol{W} \boldsymbol{S} \boldsymbol{J}_{all}^{ZX}) \quad (37)$$

Here $\boldsymbol{S} = diag[s_1, s_1, \cdots, s_i, s_i, \cdots, s_n, s_n] \in \mathbb{R}^{2n \times 2n}$, and $\boldsymbol{J}_{all}^{ZX} = [\boldsymbol{J}_{img}^{ZX}(x_1, y_1, Z_1)^T, \cdots, \boldsymbol{J}_{img}^{ZX}(x_n, y_n, Z_n)^T]^T \in \mathbb{R}^{2n \times 2}$. By substituting (36) into (33), the estimated force is obtained as (38).

$$\begin{aligned} \boldsymbol{F}_{reac}^{dyn} &= \boldsymbol{T}^{-T} \boldsymbol{K}_{tn} \boldsymbol{I}_a - \boldsymbol{T}^{-T} \boldsymbol{T}_{dis} - \boldsymbol{M}_r \dot{\boldsymbol{v}}_r \\ &\quad + \boldsymbol{M}_r \dot{\boldsymbol{R}} \boldsymbol{v}_{obj} + \boldsymbol{M}_r \boldsymbol{R} \dot{\boldsymbol{v}}_{obj} \\ &= \boldsymbol{F}_{reac} + \boldsymbol{M}_r \dot{\boldsymbol{R}} \boldsymbol{v}_{obj} + \boldsymbol{M}_r \boldsymbol{R} \dot{\boldsymbol{v}}_{obj} \end{aligned} \quad (38)$$

The last two terms in right hand side of (38) have unique meaning, that is virtual external force, in vision-based approach. $\boldsymbol{M}_r \boldsymbol{R} \dot{\boldsymbol{v}}_{obj}$ is regarded as remote inertial force affected by dynamic object motion. The ratio of this effect can be regulated intentionally, because it is influenced through matrix $\boldsymbol{R}$ defined in (37). Therefore the matrix $\boldsymbol{R}$ can be considered as something like a visual sensitivity index against the dynamic objects. For example, in case that weighting factor sets to $w_{obj} = 0$, $\boldsymbol{R}$ become $\boldsymbol{0}$ (*zero*). If w_{obj} sets to $0 \sim 1$, an intermediate effect is selectable. Thus unique feature of vision-based approach, that is like a remote haptic property, is useful for obstacle avoidance, remote navigation through vision and so on under force-related motion controller. And the functionality depend entirely upon the way to determine the weighting factor (31). In this paper, some results of the effects of virtual external force are demonstrated in sub-section 5.3. Further analysis and its concrete applications should be discussed in future work.

5. EXPERIMENTAL RESULTS

5.1 Experimental Setup

The vision-based estimation is verified by using wheelchair-type mobile robot in Fig.7(a). Two IEEE1394 High speed cameras with 1/3inch progressive scan CCD are mounted. Two direct drive AC servo motors are employed for differential wheel drive, and they are controlled by RTLinux PC controller. Windows PC for image processing is also mounted on the robot. Two PCs are connected through Ethernet link as shown in Fig.7(b). The motion control sampling is 1ms, and estimated velocity from image processing is updated at frame rate (60Hz). Image size and cell block size are $320 \times 240 pixel$ and $27 \times 27 pixel$ respectively. For stable calculations of OFV and DV, the texture sheet surrounds the workspace of mobile robot in the experiments.

For all of experiments, the robot motion is controlled by velocity feedback as shown in (39).

$$\dot{\boldsymbol{v}}_r = \boldsymbol{K}(\boldsymbol{v}_r^{cmd} - \hat{\boldsymbol{v}}_r) \quad (39)$$

where $\boldsymbol{K} = diag[K_v \;\; K_\omega]$ means the feedback gain matrix including translational/rotational velocity feedback gain K_v and K_ω respectively. And $\boldsymbol{v}_r^{cmd}$ is velocity command. The calculated acceleration $\dot{\boldsymbol{v}}_r$ is inputted into wheel motion controller with reaction force observer as shown in Fig.5.

5.2 Actual Reaction Force Estimation

To confirm the validity of estimated force, human pushes the robot with constant force $40N$ manually by using spring measure in translational forward direction. At first, in stationary state $\boldsymbol{v}_r^{cmd} = 0$ with no dynamic objects in the field of view, the estimated force and resulted motion are plotted in Fig.8(a) and (b) respectively. The force is inputted from 2.0sec. From Fig.8(a), although some delays and noisy oscillations are appeared, external force is well estimated.

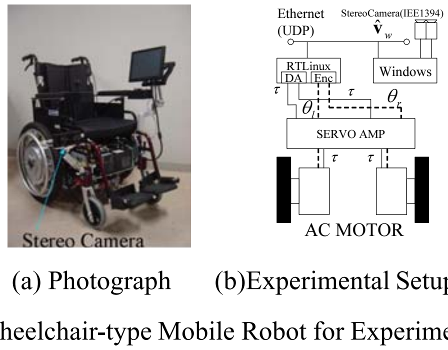
Under constant accelerated motion ($0.25 m/s^2$), the results are also plotted in Fig.9. While the external force is inputted from 1.5sec in same way. the external force is well estimated. However some negative force is detected from 0.5sec to 1.5sec while no external force period. In vision-based approach, high image resolution is required enough to detect the OFV especially in low speed condition. From 0.5sec to 1.5sec, the velocity estimation error due to low speed causes some undesirable force, which corresponds to the incorrect effect of third term in right hand side of (28). To overcome this problem, further developments for vision-based motion estimation are required in the proposed approach.

5.3 Virtual Force Effects by Dynamic Object

To confirm virtual effects from dynamic object motion in the field of view, one flat plate object is put at the distant front of robot as shown in Fig.6. It is moved sinusoidally by manual operation along translational velocity axis in robot space. Two weighting values w_{obj} in (31) are tested as shown in Fig.10.

Fig.10(a) and (b) show the results with no actual external force by human. In case $w_{obj} = 0$, the estimation becomes nearly zero. Because visual effects of an object motion is removed by weighting factor in motion estimator (19). On the other hand, Fig.10(b) in case $w_{obj} = 0.5$ shows the results of appearing the effects of virtual force according to sinusoidal object motion from 2.0sec. As shown in Fig.10(c), while pushing constant external force (approx. 100N) by human, it is found that virtual force is an additional effect with estimating actual external force. In this case, the object moved sinusoidally from 3.5sec. If an object exists at more distant position (with no actual external force), the virtual force becomes small as shown in Fig.10(d). Because the occupied image area by an object is reduced in the field of view.

This features may be more useful with additional functions of the intelligent scene analysis which is related to various robot motion such as avoidance, following action, cooperative motion and so on. Although we employed a simple detection

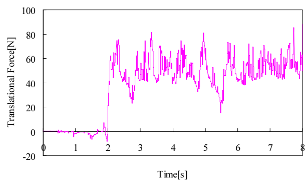


(a) Photograph (b)Experimental Setup

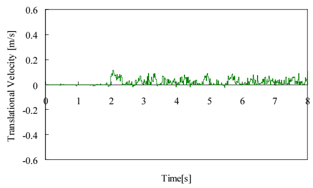
Fig. 7. Wheelchair-type Mobile Robot for Experiments

Table 1. Parameters for experiment

Feedback Gain $\boldsymbol{K}$	$diag[4 \;\; 4]$	M_w^{nom}	diag[0.5 , 0.5]
Observer Gain $g_{dis}(rad/s)$	40	f	3.5mm
Reaction Force Observer Gain $g_{est}(rad/s)$	12	L	75mm
		W	0.61m
Weight of Robot (kg)	90	R	0.254m

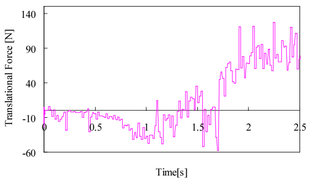


(a) Estimated External Force

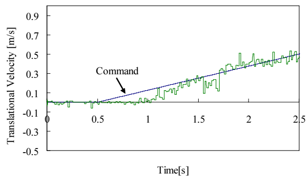


(b) Estimated Velocity

Fig. 8. Results of External Force Estimation under stationary state



(a) Estimated External Force



(b) Estimated Velocity

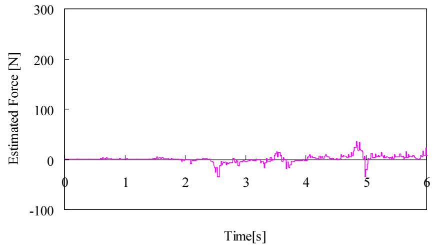
Fig. 9. Results of External Force Estimation under constant accelerated motion

method for dynamic obstacle in this paper, more precise and robust recognition will be expected for realizing this feature in practical applications.

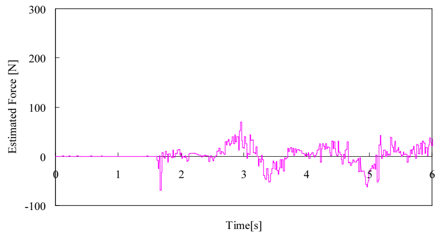
6. CONCLUSIONS

The paper proposes an approach of vision-based external force estimation for mobile robots. The formulations for designing both of observer-based force estimator and image processing are presented detailedly. And it is found analytically and experimentally that virtual effects from dynamic environments are included in estimated force and it can be regulated by changing the weight factor of each OFV in motion estimator. Further developments of image processing are meaningful for faster motion and force response.

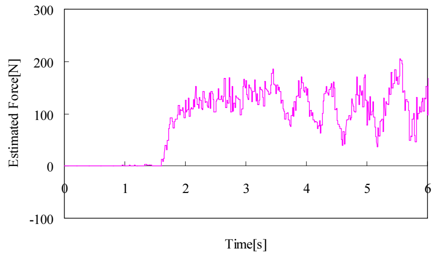
The virtual force from dynamic environments may be useful idea for sophisticated interactions between robot and environments. And it is important issue for more dense relationship of force and visual sensing in order to design the intelligent robotic systems. From practical point of view, the concrete applications need to be discussed and developed in future study.



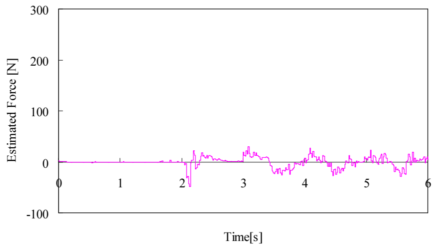
(a) Weighting Factor $w_{obj} = 0$



(b) Weighting Factor $w_{obj} = 0.5$



(c) With Actual External Force ($w_{obj} = 0.5$)



(d) Long Distant Case ($w_{obj} = 0.5$)

Fig. 10. Results of External Force Estimation in case a dynamic object exists

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