Design of an Active Bumper with a Series Elastic Actuator for Pedestrian Protection of Small Unmanned Vehicles

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Abstract. When autonomous unmanned vehicles are operated on sidewalks, the vehicles must have high safety standards such as avoiding injury when they come in contact with pedestrians. In this study, we established a design for preventing serious injury when such collisions occur. We designed an active bumper with a series elastic actuator, with the goal of avoiding serious injury to a pedestrian in a collision with a small unmanned vehicle. The series elastic actuator comprised an elastic element in series with a table driven by a ball screw and servo motor. The active bumper was used to control the contact force between a vehicle and a pedestrian. The optimal force for minimizing the deflection of the object of the collision was derived, and the actuator controlled to apply this optimal force. Numerical simulations showed that the active bumper was successful in improving the collision safety of small unmanned vehicles.

1. Introduction
When small autonomous unmanned vehicles are operated on sidewalks, it is difficult to completely avoid accidental contact with pedestrians. In this study, we established a design for preventing serious injury when such collisions occur. Our design used an active bumper with a series elastic actuator to control the contact force between the vehicle and pedestrian. A series elastic actuator comprises an elastic element in series with a table driven by a ball screw and servo motor. In a series elastic actuator, the contact force is proportional to the series elastic deflection. A series elastic actuator [1]-[3] allows (1) a precisely desired contact force to be achieved because the series elastic element converts the control of the contact force to the position control of the table; (2) the active bumper can be made lightweight by using a small servo motor with high gear reduction at the ball screw; and (3) the elastic element can achieve passive collision safety without requiring control.

2. Active Bumper
2.1. Dynamic Model
Figure 1 shows a model of a vehicle with an active bumper approaching an object with which it will collide. In this figure, \( m_c \) is the mass of the vehicle, \( m_b \) is the mass of the bumper, \( f \) is the control input, which is the force applied to the bumper, \( m \) is the mass of the object of the collision, \( k \) is the contact stiffness between the bumper and the object of the collision, and \( c \) is the contact damping between the bumper and the object of the collision. The displacement of the vehicle mass \( m_c \) is given by \( x_c \), the displacement of the bumper mass \( m_b \) is given by \( x_b \), and the displacement of \( m \) is given by \( x \). The coordinate origin in any displacement is established when the bumper collides with the object.
The equations of motion of the dynamic model shown in figure 1 were obtained as follows. After contacting the object,

\[ m_c \ddot{x}_c = -f \]
\[ m_b \ddot{x}_b = -k (x_b - x) - c (\dot{x}_b - \dot{x}) + f \]
\[ m\ddot{x} = k (x_b - x) + c (\dot{x}_b - \dot{x}) \]

Defining the state vector as

\[ \mathbf{x} = [x_c \ x_b \ x \ \dot{x}_c \ \dot{x}_b \ \dot{x}]^T \]

the state equation after contact with the object was obtained by

\[ \dot{\mathbf{x}} = A_a \mathbf{x} + B_a f \]

where

\[ A_a = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & -\frac{k}{m} & \frac{k}{m} & 0 & -\frac{c}{m} & \frac{c}{m} \\
0 & \frac{k}{m} & -\frac{k}{m} & 0 & \frac{c}{m} & -\frac{c}{m} \\
0 & \frac{m_b}{m} & -\frac{m_b}{m} & 0 & \frac{m_b}{m} & -\frac{m_b}{m}
\end{bmatrix} \quad B_a = \begin{bmatrix}
0 \\
0 \\
0 \\
-\frac{1}{m_c} \\
\frac{1}{m_b} \\
0
\end{bmatrix} \]

2.2. Optimization

The control input \( f \) was designed to minimize the object deflection. The initial velocities of the vehicle mass \( m_c \) and the bumper mass \( m_b \) were set to 1.5 m/s, which is slightly faster than a human’s walking speed. The initial velocity of the object was set to 0 m/s. The deflection of the object \( d \) was defined as

\[ d = x_b - x \]

The maximum deflection of the object \( d_{max}^d = \max d \). The formulation of the optimization problem led to the following minimization problem:

\[ \min_f d_{max}^d \]

subject to

\[ d_{min}^d \leq d_b \leq d_{max}^d \]
Table 1. Values in physical model and optimization (active bumper).

| Parameter | Unit | Value | Parameter | Unit | Value |
|-----------|------|-------|-----------|------|-------|
| $m_c$     | kg   | 15    | $d_b^{\text{min}}$ | m    | -0.05 |
| $m_b$     | kg   | 0.2   | $d_b^{\text{max}}$ | m    | 0.05  |
| $m$       | kg   | 9     | $f^{\text{min}}$  | N    | -100  |
| $k$       | N/m  | 1000  | $f^{\text{max}}$  | N    | 100   |
| $c$       | Ns/m | 10    |           |      |       |

\[ f^{\text{min}} \leq f \leq f^{\text{max}} \]  \hspace{1cm} (10)

where $d_b$ is the relative displacement of the bumper defined as

\[ d_b = x_c - x_b \]  \hspace{1cm} (11)

2.3. Simulation results

The parameter values used in the simulation are shown in table 1. Figure 2 shows the simulation results. The bumper of the vehicle collided with the object at 0 s. Figure 2 (a) shows the bumper force or the control input, figure 2 (b) shows the relative displacement of the bumper as defined by Eq. 11, and figure 2 (c) shows the deflection of the object of the collision as defined by Eq. 7. In figure 2 (d), the thick line shows the displacement of the vehicle, the thin line indicates the displacement of the bumper, and the dashed line shows the displacement of the object of the collision.

From figure 2 (a) it can be seen that the control input was bang-bang-like immediately after the collision. The control input of 100 N was the restraint of the maximum force $f^{\text{max}}$ in the optimization from 0 s to 0.01 s and -100 N was the restraint of the minimum force $f^{\text{min}}$ in the optimization from 0.01 s to 0.015 s. In response to the control input, the bumper displaced significantly immediately after impact, reaching about -0.03 m at 0.015 s (figure 2 (b)). The deflection of the object increased significantly after the point of impact to about 0.06 m at 0.015 s (figure 2 (c)). Figure 2 (a) shows that the control input remained at 60 N from 0.015 s to 0.15 s. The relative displacement of the bumper reached a maximum of 0.05 m at about 0.15 s (figure 2 (b)), and the deflection of the object was similar, at 0.06 m (figure 2 (c)). Figure 2 (d) shows that the velocity of the vehicle decreased as its displacement increased to about 0.28 m at 0.30 s. In contrast, the velocity of the object increased as its displacement increased to 0.27 m at 0.30 s. The relative velocity between the vehicle and the object was 0 at about 0.15 s.

3. Active Bumper with Series Elastic Actuator

3.1. Dynamic Model

Figure 3 shows the model of an object of collision and a vehicle with an active bumper using a series elastic actuator comprising a ball screw and an elastic element. $m_s$ is the mass of the moving parts of the ball screw mechanism including a nut, and $k_s$ is the stiffness of the elastic element. $l$ is the ball screw lead, $I$ is the moment of inertia of the ball screw mechanism, and $\tau$ is the control input, or the torque applied to the ball screw. The displacement of the moving parts of the ball screw mechanism is $x_s$. The coordinate origin of each displacement was established when the bumper collides with the object. The relationship between the ball screw rotation angle $\theta$, and the relative displacement of the moving part of the ball screw mechanism from the vehicle was derived by

\[ \theta = \frac{2\pi}{l} (x_s - x_c) \]  \hspace{1cm} (12)
Figure 2. Simulation results of the active bumper.

Defining the state vector as

$$\mathbf{x}_s = [x_c \ x_b \ x \ \dot{x}_c \ \dot{x}_s \ \dot{x}_b \ \ddot{x}]^T$$

the state equation after contact with the object was obtained as

$$\dot{\mathbf{x}}_s = A_s \mathbf{x}_s + B_s \tau$$
The matrices were as follows:

\[
A_s = \begin{bmatrix}
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & -\frac{4\pi^2 I_k}{m} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{4\pi^2 I_k}{m} & k & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{m}{k} & m & k & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

(15)

\[
B_s = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
-\frac{2\pi l m_s}{m} \\
-\frac{2\pi l m_c}{m} \\
-\frac{\bar{m}}{m} \\
0 \\
0
\end{bmatrix}
\]

(16)

where

\[
\bar{m} = m_c m_s I^2 + 4\pi^2 I (m_c + m_s)
\]

(17)

3.2. Control method

The optimal force applied to the bumper \(m_b\) was obtained as discussed in the Sec. 2.2. In the series elastic actuator, the force applied to the bumper was determined by the stiffness \(k_s\) and the relative displacement \(d_{sb}\) where

\[
d_{sb} = x_s - x_b
\]

(18)

Figure 3. Model of vehicle with active bumper using a series elastic actuator and object of collision.
Figure 4. Simulation results for the active bumper with a series elastic actuator.

The applied force $f$ was

$$f = k_s d_{sb}$$  \hspace{1cm} (19)

The desired value of relative displacement $d_{sb}^d$ used to determine the optimal force $f_{opt}$ was given by

$$d_{sb}^d = \frac{f_{opt}}{k_s}$$  \hspace{1cm} (20)

and the series elastic actuator was controlled to the desired value $d_{sb}^d$. A simple control scheme was applied, as follows:

$$\tau = -K_p (d_{sb} - d_{sb}^d) - K_v \dot{d}_{sb}$$  \hspace{1cm} (21)

where $K_p$ and $K_v$ are control gains.

3.3. Simulation results

The parameter values used in the simulation are given in table 2. We set the control gains at $K_p = 4000$ and $K_v = 10$ by trial and error. Figure 4 shows the result when the active bumper with the series elastic actuator was used. The bumper of the vehicle made contact with the object at 0 s.

Table 2. Values in the physical model (active bumper with series elastic actuator).

| Parameter | Unit | Value | Parameter | Unit | Value |
|-----------|------|-------|-----------|------|-------|
| $m_c$    | kg   | 14.8  | $k_s$    | N/m  | 20000 |
| $m_s$    | kg   | 0.2   | $k$      | N/m  | 1000  |
| $m_b$    | kg   | 0.2   | $c$      | Ns/m | 10    |
| $m$      | kg   | 9     | $I$      | kg m$^2$ | $1 \times 10^{-5}$ |
|          |      |       | $l$      | m    | 0.01  |
Figure 4 (a) shows the relative displacement of the actuator given by Eq. 18 and the desired values obtained from Eq. 20. Although the difference between $d_{sb}$ and $d^d_{sb}$ was large, $d_{sb}$ was almost the same as $d^d_{sb}$ by 0.025 s. Figure 4 (b) shows the deflection of the object. The time response of the object was almost the same in the case with the active bumper shown in figure 2 (c). The maximum deflection of the object was 0.06 m at 0.05 s.

4. Conclusions

We designed an active bumper with a series elastic actuator, with the goal of avoiding serious injury to a pedestrian in a collision with a small unmanned vehicle. The series elastic actuator comprised an elastic element in series with a table driven by a ball screw and servo motor. The active bumper was used to control the contact force between a vehicle and a pedestrian. The optimal force for minimizing the deflection of the object of the collision was derived, and the actuator controlled to apply this optimal force. Numerical simulations showed that the active bumper was successful in improving the collision safety of small unmanned vehicles.

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