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# Vision Based Active Antenna

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## Abstract

*This paper proposes the Vision Based Active Antenna (VBAA) that can detect the contact force, the stiffness of the environment, and the contact location between an insensitive elastic antenna and an environment, through the observation of the antenna's shape by a camera. We show that both the contact location and the contact force can be estimated by measuring two arbitrary points on the antenna after a pushing motion, even though the exact contact point is hidden by occlusion. By considering the geometrical relationship between the virtual (without environment) and the real (with environment) displacements of the contact point, the stiffness of the environment can also be estimated, while our conventional Active Antenna can not do. We present the basic working principle of the VBAA and give experimental verification.*

## I Introduction

The Vision Based Active Antenna (VBAA) is a new sensing system enabling us to detect the contact location between an insensitive elastic antenna and an environment, the contact force, and the stiffness of the environment through observation of the antenna's shape. The VBAA is simply composed of one insensitive elastic antenna, one actuator to rotate the antenna, one position sensor to measure the rotation angle of the antenna, and one CCD camera to observe the antenna's shape, as shown in Fig.1. In our former work, we have shown that if the environment is rigid, the contact location is a function of the rotational compliance of the antenna in contact with the environment, and that it can be obtained by utilizing the outputs from both joint position and torque sensors. Such a sensing system has been termed the Active Antenna [1, 2]. This idea has also been extended to a 3D version [3]. A big advantage of the Active Antenna is that a contact point is obtained through a surprisingly simple active motion, while sophisticated active motions should be prepared in most contact sensing methods in order to avoid a large interaction force between the sensor and the environment to be sensed. This is because the flexibility of the antenna itself successfully relaxes the contact force, even under a large positional error. However, the Active Antenna cannot work appropriately in a compliant environment, since the sensor system is not able to break down the measured compliance into that coming from the antenna itself and that coming from the environment. The difficulty of decomposition comes from the sensor system utilizing only local information, such as the joint torque and the joint angular displacement, but not taking any global information into consideration. This is the reason why a vision system is introduced into the VBAA. An active motion is imparted to the antenna for environment sensing. The camera continuously observes the antenna's shape. By observing the shape distortion from it's original straight line position, the sensor system can detect any initial contact with an environment. With further active motion, the antenna deforms according to the pushing angle, the contact location, and the environment's stiffness. The pushing angle after contact can be regarded as input for the VBAA, and the antenna's shape obtained through the CCD camera can be regarded as output. By an input-output relationship, the VBAA can detect the contact distance, the contact force, and the environment's stiffness. In order to measure stiffness, a position sensor and a force sensor are generally necessary in addition to the actuator which imparts an active motion. It can be understood that in the VBAA, a force is equally detectable through the observation of the elastic deformation of the antenna by a camera. Without elasticity of the antenna, it is impossible to evaluate both the contact force and the environment's

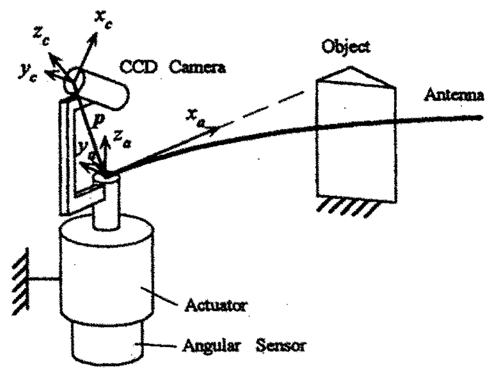



Fig.1: An overview of VBAA.

stiffness, and so such elasticity of the antenna is quite essential to the VBAA.

In this paper, we show that even when the exact contact point is hidden by occlusion, the VBAA can still provide both the contact point and the contact force if two arbitrary points on the antenna are observed.

# II Related Works

A simple flexible beam sensor can take the form of a short length of spring piano wire or hypodermic tubing anchored at the end. When the free end touches an external object, the wire bends. This can be sensed by a piezoelectric element or by a simple switch [4]. A more elaborate sensor is described by Wang and Will [5]. Long antennae-like whisker sensors were mounted on the SRI mobile robot, Shakey [6], and on Rodney Brook's six-legged robot insects [7]. Hirose, et.al. discussed the utilization of whisker sensors in legged robots [8]. Similarly shaped whiskers have been considered for the legs of the Ohio State University active suspension vehicle [9]. Russell developed a sensor array [10] by mounting whisker sensors on a mobile robot, and succeeded in reconstructing the shape of a convex object followed by the whisker. In his work, it is assumed that the whisker tip is always in contact with the environment, and that when whisker other than the tip contacts the environment, it is assigned to a failure mode. The major difference between previous works [4]–[10] and ours is that the VBAA can detect not only a contact point between the antenna and the environment, but also the environment's stiffness, while previous works do not.

There are several works combining both tactile and vision sensors to take most advantage of each sensor. For example, Stansfield presented a robotic perceptual system which utilizes passive vision and active touch [11]. Allen proposed an object recognition system that uses passive stereo vision and active exploratory tactile sensing [12]. These works utilized two different kinds of sensors to increase sensing ability. In the VBAA, a vision sensor is utilized for indirectly evaluating the contact force and the contact point.

# III Basic Working Principle of VBAA

## (A) Importance of the elasticity of antenna

Now, let us assume that the antenna of the VBAA is a rigid beam with scale. For the contact point detection, the CCD camera will be able to, in principle, directly read the scale in contact with the environment, if a good working condition is prepared for visual sensing. However, because of occlusion or lighting problems, providing good conditions for a vision system is usually difficult and, as a result, the real contact point is often hidden or unreadable in ambiguous scene. Furthermore, when the antenna makes contact with a compliant environment, it is particularly difficult to find an exact contact point since it sinks into the surface. Thus, the VBAA using a rigid beam does not seem to work successfully in a practical environment. Let us now assume that the antenna is an elastic one whose force-deformation behavior is known in advance. When such an antenna makes contact with an environment, it deforms according to the contact point, the pushing angle and the environment's stiffness. The antenna deforms between the base and the contact point, while the remaining part of the antenna keeps in a straight line. By utilizing this information, the VBAA can evaluate the contact point. Later, we will show that two arbitrary points on the antenna are necessary and sufficient for determining the antenna's unique shape. This is the great advantage in utilizing an elastic antenna, since the sensor system does not require any information from the exact contact point. Thus, the VBAA using an elastic antenna could be highly robust for occlusion.

## (B) Main assumptions

Main assumptions taken here are as follows:

Assumption 1: The antenna's motion is limited to a plane.

Assumption 2: The deformation of the antenna is small enough to ensure that the antenna's behavior obeys the force-deformation relationship obtained by linear theory.

Assumption 3: The environment (or object) to be sensed is stationary during active motions.

Assumption 4: The elongation of the antenna due to a unit axial force is negligibly small compared with the deflection due to a unit bending force.

Assumption 5: Before applying an active motion, the antenna is already in contact with an environment with zero force.

Assumption 6: The antenna is connected to the actuator shaft at the center of rotation.

Assumption 7: All pixels concerning the antenna are already extracted from the scene.

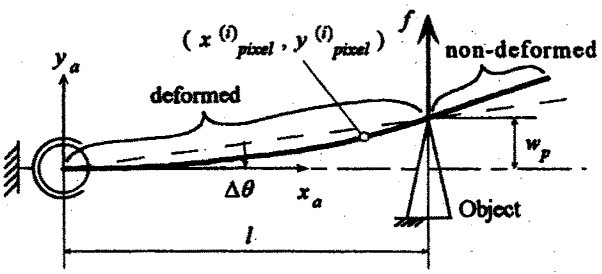



Fig.2: Top view of the VBAA.

### (C) Contact distance sensing and contact force sensing

Since the antenna's deformation is restricted in the $x_a y_a$-plane with assumption 1, the main problem hereafter is to search for the contact point between the antenna and an environment in the $x_a y_a$-plane. The relationship between the antenna's shape and the contact force is given by,
(i) the deformed part

$$y_a = \frac{f}{6EI}(3l - x_a)x_a^2 \quad , \quad (0 < x_a \le l) \tag{1}$$

(ii) the non-deformed part

$$y_a = \frac{f}{6EI}(3x_a - l)l^2 \quad (l \le x_a) \tag{2}$$

where $l$, $f$, $E$ and $I$ are the contact distance, the contact force, the elasticity of the antenna and the second order moment of the cross section of the antenna, respectively.

The following is an important theorem.

**[Theorem 1]** Let $P_1$ $(x_1, y_1)$ and $P_2$ $(x_2, y_2)$ be two different points on the antenna where $0 < x_1 < x_2$. The contact distance and the contact force are uniquely determined by these two points.

Proof: There are three possible cases, two points appear in the deformed part, in the non-deformed part, or two points exist in the two different parts.

(i) Two points from the deformed part
From eq.(1), we can obtain the following two equations.

$$y_1 = \frac{f}{6EI}(3l - x_1)x_1^2 \tag{3}$$

$$y_2 = \frac{f}{6EI}(3l - x_2)x_2^2 \tag{4}$$

where $l$ should satisfy the condition of $0 < x_1 < x_2 \le l$. From eq.(3) and (4), we can easily show a unique set of solutions in $0 < x_1 < x_2 \le l$ as follows,

$$f = 6EI\frac{x_2^2 y_1 - x_1^2 y_2}{x_1^2 x_2^2 (x_2 - x_1)} \tag{5}$$

$$l = \frac{x_1^3 y_2 - x_2^3 y_1}{3(x_1^2 y_2 - x_2^2 y_1)} \tag{6}$$

Note that $x_2 - x_1 \neq 0$, $x_1^2 y_2 - x_2^2 y_1 \neq 0$, $x_1 \neq 0$, $x_2 \neq 0$ under $0 < x_1 < x_2 \le l$.

(ii) Two points from the non-deformed part
In this case, we can obtain the following two equations.

$$y_1 = \frac{f}{6EI}(3x_1 - l)l^2 \tag{7}$$

$$y_2 = \frac{f}{6EI}(3x_2 - l)l^2 \tag{8}$$

where $l$ should satisfy the condition of $0 < l \le x_1 < x_2$. From eq.(7) and (8), we can introduce a unique set of solutions in $0 < l \le x_1 < x_2$ as follows,

$$f = 2EI\frac{-(y_1 - y_2)^3}{9(x_2 - x_1)(x_1 y_2 - x_2 y_1)} \tag{9}$$

$$l = \frac{3(x_1 y_2 - x_2 y_1)}{y_2 - y_1} \tag{10}$$

Note that $x_2 - x_1 \neq 0$, $y_2 - y_1 \neq 0$, $x_1 y_2 - x_2 y_1 \neq 0$ under $0 < l \le x_1 < x_2$.

(iii) One from each of the deformed and non-deformed parts
Let $P_1$ and $P_2$ be points in the deformed part and the non-deformed part, respectively. Without any generality, we can assume $0 < x_1 \le l \le x_2$ and $x_1 \neq x_2$. In this case, eq.(3) and (8) exist. From these equations, we obtain,

$$g(l) = y_1 l^3 - 3x_2 y_1 l^2 + 3x_1^2 y_2 l - x_1^3 y_2 = 0 \tag{11}$$

Equation (11) is the third order equation with respect to $l$. From eq.(11), we can easily show eqs.(12) and (13) under $0 < x_1 \le l \le x_2$, $x_1 \neq x_2$ and $0 < f$.

$$\lim_{l \to -\infty} g(l) = -\infty \tag{12}$$

$$\lim_{l \to +\infty} g(l) = +\infty \tag{13}$$

Now, let us examine the sign of $g(x_1)$ and $g(x_2)$. $g(x_1)$ and $g(x_2)$ can be rearranged in the following forms.

$$g(x_1) = \frac{f}{6EI}(l - x_1)x_1^3\{(3x_2 - x_1)(l - x_1) + l(x_2 - x_1) + 2l(x_2 - l)\} \tag{14}$$

$$g(x_2) = -\frac{f}{6EI}x_1^2(x_2 - l)\{l(2x_2 + l)(x_2 - x_1) + 2lx_2(x_2 - l) + 2x_2^2(l - x_1)\} \tag{15}$$

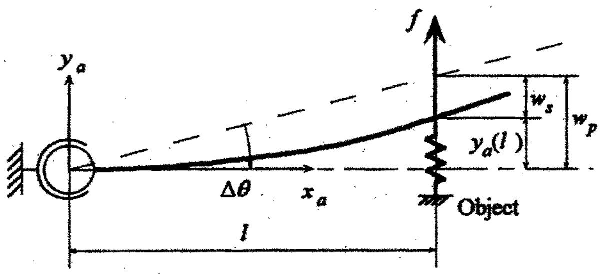
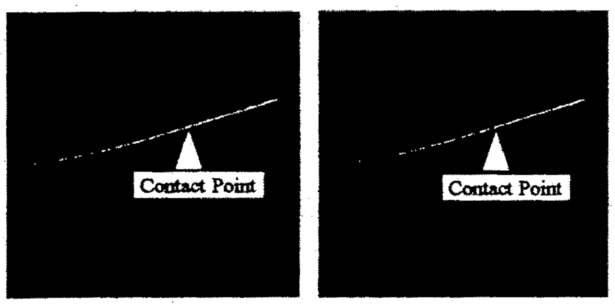



Fig.3: Stiffness sensing by the VBAA.




(a) Digitized image (b) Binary image

Fig.4: Caputured picture.

Under the condition of $0 < x_1 \leq l \leq x_2$, $x_1 \neq x_2$ and $0 < f$, we can easily show $g(x_1) \geq 0$ and $g(x_2) \leq 0$. Conditions (12), (13), $g(x_1) \geq 0$ and $g(x_2) \leq 0$ ensures that we always have one real root between $x_1$ and $x_2$, while there are three real roots (double roots can be allowed) over the whole range.

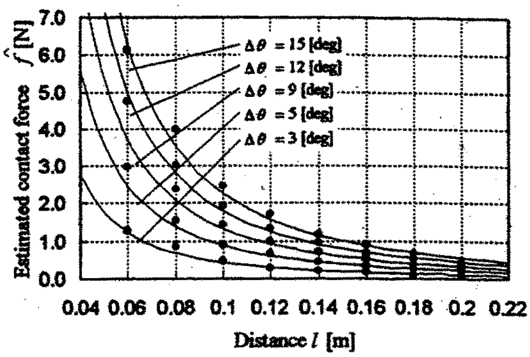
Theorem 1 tells us that even when the exact contact point is hidden due to the occlusion, for example, both the contact length and the contact force can be estimated by utilizing the remaining part of the antenna's shape taken in through the CCD camera.

## (D) Stiffness sensing

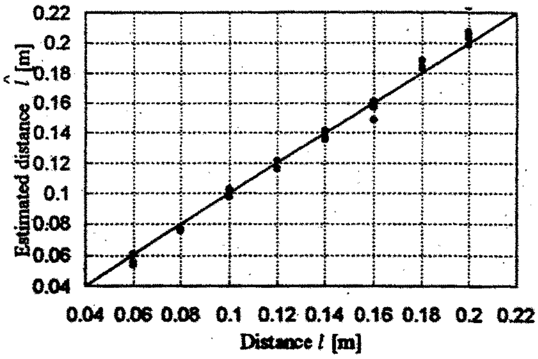
Since the VBAA can estimate both the contact distance and the contact force continuously, it can evaluate the environment's stiffness as well. If the environment is highly stiff, the contact point on the environment does not move with respect to the absolute coordinate system. This can be judged by examining the following condition.

$$\hat{w}_s = w_p - y_a(\hat{l}) \tag{16}$$

where $\hat{w}_s$ is the estimated shift of the contact point with respect to the absolute coordinate system, and $w_p = l\Delta\theta$ is the virtual shift of the contact point on the antenna assuming that there is no environment,




(a)




(b)

Fig.5: Experimental results for a stiff environment.

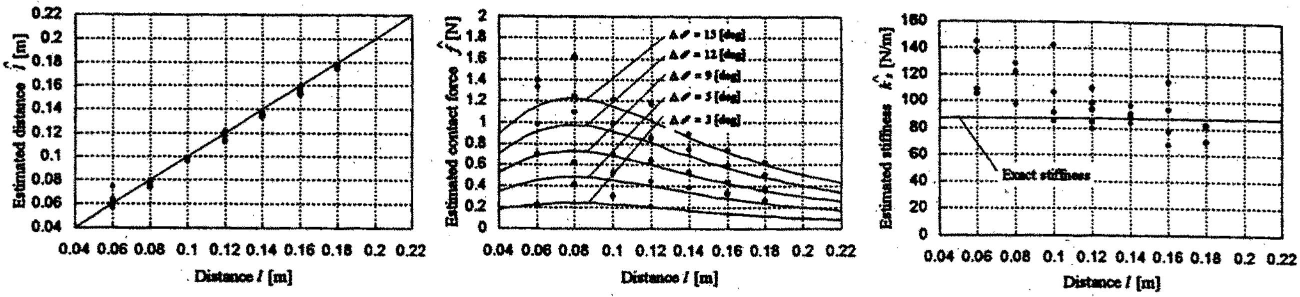
and where $\Delta\theta$ is the pushing angle. For $\hat{w}_s \neq 0$, the environment is judged to be compliant, while for $\hat{w}_s = 0$, it has an extremely large stiffness value. Now, suppose $\hat{f}$ and $\hat{l}$ be the estimated contact force and contact distance, respectively. For $\hat{w}_s \neq 0$, we can evaluate the stiffness by

$$\hat{k}_s = \frac{\hat{f}}{\hat{w}_s} = \frac{\hat{f}}{w_p - y_a(\hat{l})} \tag{17}$$

Note that the stiffness sensing does not make any influence on the contact point sensing and the contact force sensing, and it is independently evaluated after $\hat{f}$ and $\hat{l}$ are estimated.

# IV Experimental Verification

The image data are fed into the computer through a CCD camera with 256 × 256 dots and 8bits gray scale. For easily distinguishing the antenna from the environment, we use a white stainless antenna with a diameter of 1.4mm and a length of 200mm. We believe that one of the big advantages of VBAA is that we can paint the antenna so that it may be easily distinguished from the environment. In order to suppress




(a) (b) (c)

Fig.6: Experimental results for a compliant environment.

the sensing error caused by digitalization, we use all data concerning the antenna instead of utilizing just two points on the antenna. Let us define $h(f, l, x_a)$ as follows

$$h(f, l, x_a) = \begin{cases} \dfrac{f}{6EI}(3l - x_a)x_a^2 & (0 < x_a \leq l) \\ \dfrac{f}{6EI}(3x_a - l)l^2 & (l \leq x_a) \end{cases} \tag{18}$$

Also, let us define $e(f, l)$ by eq.(19).

$$e(f, l) = \sum_{i=1}^{n} \left\| \boldsymbol{r}_{pixel}^{(i)} - \boldsymbol{r}_a \right\|^2 \tag{19}$$

where $\boldsymbol{r}_{pixel}^{(i)} = (x_{pixel}^{(i)}, y_{pixel}^{(i)})^t$ denotes the position of pixel $i$ on the antenna obtained by vision and $\boldsymbol{r}_a = (x_{pixel}^{(i)}, h(f, l, x_{pixel}^{(i)}))^t$ denotes an arbitrary point on the function given by eq.(18). By applying the least square method, $f$ and $l$ which minimizes $e(f, l)$ can be obtained. Figure 5 shows the experimental results for a stiff environment, where (a) and (b) denote the estimated contact distance and the estimated contact force, respectively. The real lines and circles show the theoretical analysis and the experimental data, respectively. The agreement between analysis and experiments is fairly good. Figure 6 shows the experimental results for a compliant environment, where (a), (b) and (c) are the estimated contact distance, the estimated contact force and the estimated stiffness, respectively. For a compliant environment, experimental data for both contact distance and force exist slightly away from the lines expected by the analysis. This is partly caused by the difficulty of these experiments compared with those for a rigid environment. As shown in Fig.6(c), the stiffness is badly estimated when the contact happens particularly close to the base. This is because the estimation error of $w_s$ makes a large sensing error on stiffness evaluation when $w_s$ is small (see eq.(17)).

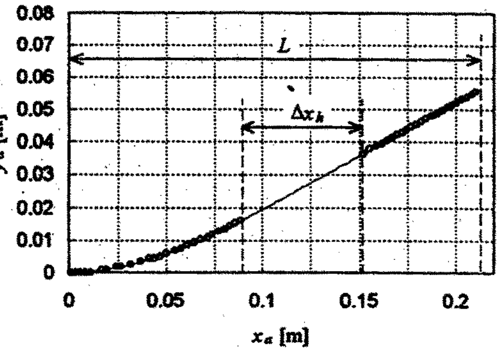



Fig.7: An example data having the occlusion.

In order to evaluate the effect of occlusion, we purposely omit the measured data as shown in Fig.7, where $\Delta x_h$ denotes the $x_a$ directional distance in which the data on the antenna are removed. Figure 8 shows various results when all the data are not always available, where the horizontal axis denotes the availability ratio $AR$ which is given by

$$AR = \frac{L - \Delta x_h}{L} \tag{20}$$

where $L$ is the $x_a$ component of the antenna tip. Since the deformation in the $y_a$ direction is extremely small compared with the antenna length, $L$ is almost equal to the antenna length in the straight line. Note that theoretically the VBAA can compute the contact length and the contact force if two arbitrary points are given. Because of this fact, even when more than 65% of data are removed, sufficiently high sensing accuracies are kept in every case. Another interesting tendency is that we can keep the accuracy relatively good when utilizing the data with the inclusion of the tip part of the antenna. This is because one pixel difference makes a large error on the curve estimation for the contact point close to the base, while it does not for the contact point close to the tip.

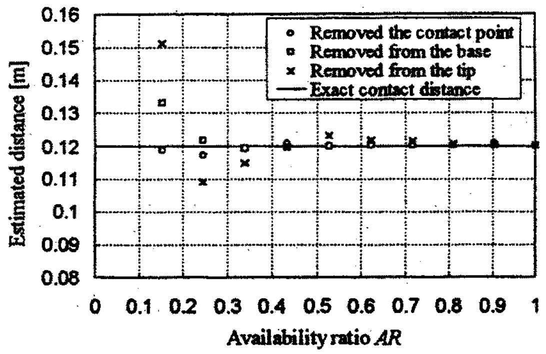



Fig.8: The effect of occlusion on the sensing error.

## V Discussions

The vision sensor is a popular and powerful tool to observe a scene in front of a robot. A big advantage of such a vision system is that it can easily obtain global information, while the tactile sensor can detect local information alone. Upon using vision, however, we have to be very careful with both occlusion and lighting problems. The problem concerning occlusion will often appear when the environment is compliant and the antenna sinks into it during a pushing motion. Since the CCD camera takes a scene from the top view, the exact contact point on the antenna and its neighborhood will be often hidden. The VBAA can overcome such an undesirable situation, since it does not need the scene including the exact contact point. Two arbitrary points on the antenna can theoretically determine the full shape of the antenna and, as a result, provide the contact force as well as the contact point. The contact force is estimated by utilizing the force-deformation relationship, while the contact point is evaluated from the geometrical relationship alone.

Now, let us consider a couple of factors which influence the sensing accuracy of the VBAA. The sensing accuracy strongly depends on how accurately we can reproduce the antenna's shape from the digitized data. The utilization of a vision system with high resolution is a reasonable way for increasing the sensing accuracy though it increases the computation burden for processing the visual data. The sensing accuracy is also influenced by the environment's stiffness. For a compliant environment, the contact force is not generated at a point, but distributed contact forces are supported by a line segment. Since we assume use of the force-deformation relationship obtained under a point contact, such a line contact will more or less bring a sensing error.

For an environment with a small curvature, the contact point on the environment will shift continuously during the pushing motion. The conventional Active Antenna [1]–[3] can never distinguish an edged environment from a curved one in principle, since they focus on local sensor information alone, such as joint torque and joint position. Theoretically, the VBAA should be able to detect a shift of contact point by observing the antenna's shape continuously, even though this paper only focuses on an edged environment to simplify discussion. We are further intending to design a VBAA with a compact size and a fast processing time.

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