Development of a Stewart Platform-based -a is Force Sensor for Robot Fingers

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Abstract: This paper describes the development of a Stewart platform-based robot force sensor with distinctive structure of ball joints. The number of ball joints is only a half of the similar style sensors, so it is possible to reduce size and weight of the sensor. The structure of ball joint is described and discussed. Furthermore, we use strain gauges, but not liner voltage differential transformers, as sensing elements, in order to reduce size and weight of the sensor. It is also proposed that beams are replaced with pipes as sensing elements of the sensor. The ball joints and sensing elements with pipes can effectively reduce the error of the sensor. A geometric analysis model is also proposed. The external force and its moment can be measured with this model. Moreover, the performance of this sensor was tested. The test results conducted to evaluate the sensing capability of the sensor is reported and discussed.

Keywords: ball joint, 6-axis Force sensor, moment sensor, Stewart platform

1. INTRODUCTION

The force/moment sensor that can measure three directional forces and three directional moments is used effectively for the force feedback control of robot field. This kind of sensor is called 6-axis force/moment sensor. A lot of proposals about 6-axis Force/moment sensor have been presented [2-5,10,12-15]. The commercialized 6-axis force/moment sensors are mainly cross structure and multi-cross structure up to now. However, this structure also has some disadvantages, such that the structures are complex, the processing of its elastic elements is difficulty and the price of the sensors is expensive.

Stewart platform was originally proposed for the flight simulator [1]. As a different kind of 6-axis force/moment sensor, Kerr proposed a Stewart platform-based force sensor with elastic links [2]. However, in the model of the Keer, the joints are not ball joints, but rigid joints. In actual situation, the legs of sensor will be twisted due to the rigid joints, when an external load acted on the sensor. Nguyen et al. proposed another Stewart plate-based force/torque sensor. The legs of the sensor are composed of pistons whose length variations are measured by six liner voltage differential transformers mounted along the pistons [3]. Kang et al. also proposed a Stewart platform-based force/torque sensor [4]. The structure of the sensor is similar to Nguyen's. The difference is deformable elastic parts. Nguyen uses pistons, Kang uses springs. Each leg of the Kang's sensor is composed of two springs, linear voltage differential transformer and a core. Although there are many advantages in the above two kind of sensors, the structure of the above is complex. There are 12 ball joints and 6 liner voltage differential transformers in a sensor. The 12 ball joints and 6 transformers occupy a larger space, it is difficult for a sensor to reduce its size.

It is still a new subject for Stewart platform style sensor to use less 12 ball joints and use some sensing elements to design a sensor in order to miniaturize a sensor and reduce the weight of sensor under the condition of stability being nearly not change.

Luo et al. also proposed a six-axis force /tactile sensor for robot finger [5]. The joints of the sensor are rigid joints and the elastic legs are thin copper beams which cross section is a thin rectangle. The elastic elements made from only a copper plate. Although the structure is simple, the beams may exist a little twisting and bending when a external load acting on the sensor. This twisting and bending may be the main cause of error.

In this paper, we propose a new structure of 6-axis force/ moment sensor for robot finger, which need only 6 ball joints. By this structure, it can be measured that the magnitude, direction of a force acted on the finger in any directions. Furthermore, magnitudes and directions of moment acted on the finger can also be measured. With using the structure of ball joints and employing thin brazen pipes as elastic elements, the problem of twisting and bending of elastic element has been mainly solved. Finally, an experiment is performed to verify our proposal.

2. ASIC MODEL

Before design the sensor, a model for the sensor was build. The finger is a half elliptic body. The sensor consists of two concentric circle in same diameter and six bars in same size as shown in Fig.1. The six bars and six ball joints compose six triangles in the same size. Two sheets of strain gages are stuck on both sides of each bar.

Before carry out analysis, we have the following assumptions:

a. The finger is a rigid body.
b. The bar of the sensor can not be curved.
c. The variations of the bar in length are very small so that they can be neglected.
e. The mass of the finger is small that it can be neglected.
f. The friction of the balls can be neglected.

We also have the following definitions: It is defined that F_x, F_y, and F_z components of external load on the finger are positive when their directions are of the same with x, y and z coordinate axis direction, respectively. Otherwise, they are negative.

2.1 The structure relations of the sensor

As shown in Fig.1, Fig.2, Fig.3, we can find that independent geometric parameters are only the length of the bar and the diameter of the circle. In other words, when the size of the diameter and height of the sensor are decided, the other geometric size will be decided.

We define that triangle ABC and lower circle meet at angle θ as shown in Fig.2. Similarly, triangles CDE, EFA and lower circle also meet at angle θ, respectively.

Define the length of each bar is b and the length of the side of regular triangle ACE is q. The lower circle is a circumscribed circle about triangle ACE. R is the radius of lower circle as shown in Fig.3.

By the sine theorem,

$$q = \sqrt{3}R . \tag{1}$$

The height of circular segment AnC is

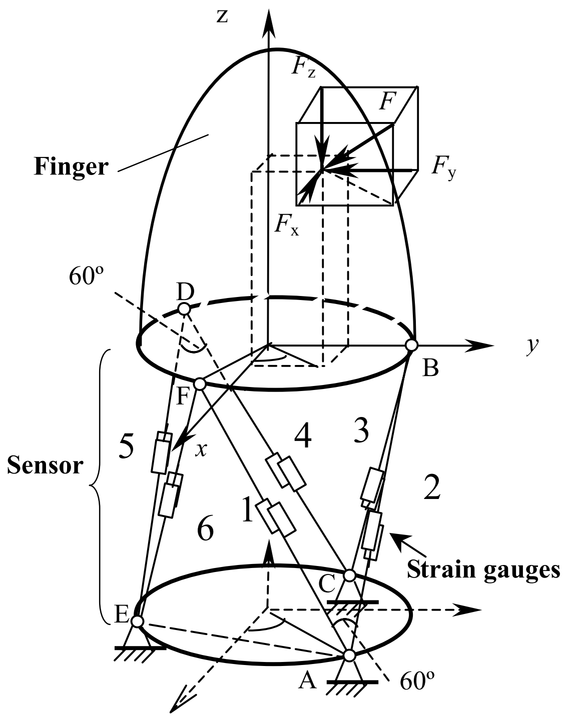

Fig. 1 Model of six-axis force/tactile sensor

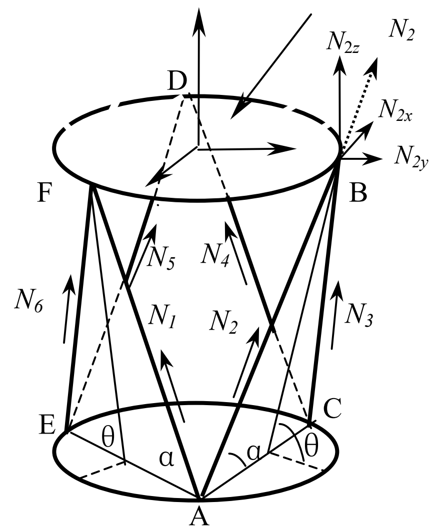

Fig. 2. geometry relation about θ

$$mn = \frac{1}{2} q \cdot tg \frac{120^\circ}{4} = \frac{q}{2\sqrt{3}} . \tag{2}$$

Comparing (1) with (2), get

$$mn = \frac{R\sqrt{3}}{2\sqrt{3}} = \frac{R}{2} . \tag{3}$$

In right triangle ABm ,

$$h = \sqrt{b^2 - \left(\frac{q}{2}\right)^2} = \sqrt{l^2 - \frac{3R^2}{4}} \tag{4}$$

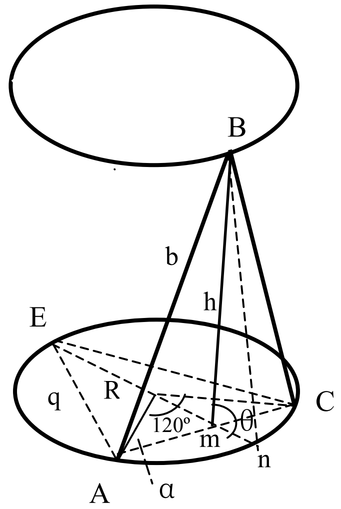

Fig.3 geometry relation of q, R, θ

In right triangle Bmn,

$$\theta = \cos^{-1}\frac{mn}{h} = \cos^{-1}\frac{R}{\sqrt{4b^2 - 3R^2}} . \tag{5}$$

Thus,

$$\alpha = \cos^{-1}\frac{Am}{AB} = \cos^{-1}\frac{R\sqrt{3}}{2b} . \tag{6}$$

2.2 The relation between the force applied on the finger and the strains of the bar

The stress of each bar is

$$\sigma_i = E\varepsilon_i \qquad (i=1\sim6) . \tag{7}$$

where σ_i is the stress of bar, ε_i is the strain of bar and E is the Young's modulus of the metal . And

$$\sigma_i = N_i / A \qquad (i=1\sim6). \tag{8}$$

where N_i being normal stress (tensile or compressive stress) and A is the cross section of the bar. Thus,

$$N_i = \sigma_i A = EA\varepsilon_i \quad (i=1\sim6). \tag{9}$$

The components of normal stress of each bar on x, y, z axis direction can get by projection methed. When we see the sensor from its upper side, we get Fig.4 which shows the projections of normal stress of each bar on x-y plane. The projections of normal stress can be projected again on x and y axis directions making use of Fig.4.

we use the below mothed to get the components of normal stress of each bar on z axis direction. First, the normal stress in each bar was projected on the medians of the triangles by α. Then the projection was projected again on the z axis direction making use of θ.

The components of normal stress in each bar on $x, y,$ and z axis directions are calculated with projection methed, respectively. They are

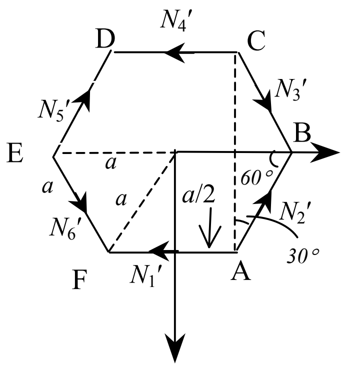

Fig.4 The projection of normal stress in each bar on x,y plane

$$N_{1x} = 0$$
$$N_{1y} = -N_1 \cos\alpha$$
$$N_{1z} = N_1 \sin\alpha \ \sin\theta \ ,$$

$$N_{2x} = -N_2 \cos\alpha \cos 30^\circ$$
$$N_{2y} = N_2 \cos\alpha \sin 30^\circ$$
$$N_{2z} = N_2 \sin\alpha \sin\theta \,,$$

$$N_{3x} = N_3 \cos\alpha \cos 30^\circ$$
$$N_{3y} = N_3 \cos\alpha \ \sin 30^\circ$$
$$N_{3z} = N_3 \sin\alpha \ \sin\theta \,,$$

$$N_{4x} = 0$$
$$N_{4y} = -N_4 \cos\alpha$$
$$N_{4z} = N_4 \sin\alpha \sin\theta \,,$$

$$N_{5x} = -N_5 \cos\alpha \ \cos\theta$$
$$N_{5y} = N_5 \cos\alpha \sin 30^\circ$$
$$N_{5z} = N_5 \sin\alpha \sin 73^\circ \ ,$$

$$N_{6x} = -N_6 \cos\alpha \ \cos 30^\circ$$
$$N_{6y} = N_6 \cos\alpha \sin 30^\circ$$
$$N_{6z} = N_6 \sin\alpha \sin 73^\circ . \tag{10}$$

By the equilibrium condition of statics[3], there are

$$F_x + \sum_{i=1}^{6} N_{ix} = 0$$
$$F_y + \sum_{i=1}^{6} N_{iy} = 0$$
$$F_z + \sum_{i=1}^{6} N_{iz} = 0 . \tag{11}$$

Therefore,

$$F_x = -\sum_{i=1}^{6} N_{ix}$$
$$= -(\cos\alpha \cos 30^\circ) EA(-\varepsilon_2 + \varepsilon_3 - \varepsilon_5 + \varepsilon_6),$$
$$F_y = -\sum_{i=1}^{6} N_{iy}$$
$$= -(\cos\alpha \sin 30^\circ) EA(-2\varepsilon_1 + \varepsilon_2 + \varepsilon_3 - 2\varepsilon_4 + \varepsilon_5 + \varepsilon_6),$$
$$F_z = -\sum_{i=1}^{6} N_{iz}$$
$$= -(\sin\alpha \sin\theta) EA(\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + \varepsilon_5 + \varepsilon_6). \tag{12}$$

The force acted on the finger (It is equal to the grapping force in value) is

$$F = \sqrt{F_x^{\ 2} + F_y^{\ 2} + F_z^{\ 2}} \ . \tag{13}$$

2.3 The direction of force

The direction of force acted on the finger shown in Fig.5, It can be calculated by

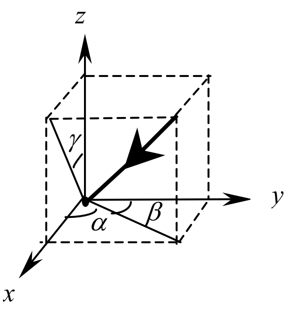

Fig.5 The direction of force

$$\alpha = \cos^{-1}\frac{F_x}{\sqrt{F_x^2 + F_y^2}},$$

$$\beta = \cos^{-1}\frac{F_y}{\sqrt{F_x^2 + F_y^2}},$$

$$\gamma = \cos^{-1}\frac{F_z}{\sqrt{F_x^2 + F_z^2}}. \tag{14}$$

2.4 The ma imum load of the sensor

According to mechanics of materials[7] , if the yield point of the material of the bar is σ_y and the safety factor is n, then the allowable stress is

$$\sigma_w = \frac{\sigma_y}{n}. \tag{15}$$

The biggest stress of each beam is

$$N_{\max} \le \sigma_w A = \frac{\sigma_y}{n} A. \tag{16}$$

where A is the cross section of the bars. From (9) and (13), the biggest load of the sensor is

$$F_{\max} = (6 \sin \alpha \sin \theta) N_{\max}. \tag{17}$$

2.5 The relation between the force acted on the finger and output voltage of the sensor

There are 6 circuits for the 6 bars. Each circuit for each bar is shown in Fig.6.

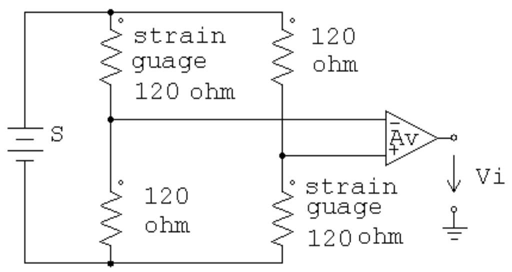

Fig. 6 circuit of each bar

The output voltage of each bar is

$$V_i = \frac{A_v K S \varepsilon_i}{2}. \tag{18}$$

where A_v is the gain of amplifier, S the supply voltage, K the coefficient of strain, ε_i the stress of each bar.

According to (13) and (18), the force acted on the finger (It is equal to grapping force in value) is

$$F = \frac{2EA}{A_v KS}\sqrt{(\cos\alpha\cos 30^\circ)^2(-V_2 + V_3 - V_5 + V_6)^2 + (\cos\alpha\sin 30^\circ)^2(-2V_1 + V_2 + V_3 - 2V_4 + V_5 + V_6)^2 + (\sin\alpha\sin\theta)^2(V_1 + V_2 + V_3 + V_4 + V_5 + V_6)^2}. \tag{19}$$

In Eq. (19), $V_1 \sim V_6$ are output votage of each bar .

2. Moment of force acted on finger and touching position of robot finger

From Fig.4 and Fig.2, the moments acted on coordiate axis of each bar are

$$\begin{aligned}
M_x(N_1) &= -N_{1z}\frac{a}{2} \\
M_x(N_2) &= N_{2z}a \\
M_x(N_3) &= N_{3z}a \\
M_x(N_4) &= -N_{4z}\frac{a}{2} \\
M_x(N_5) &= -N_{5z}\frac{a}{2} \\
M_x(N_6) &= -N_{6z}\frac{a}{2}, \\
M_y(N_1) &= -N_{1z}a\sin 60^\circ \\
M_y(N_2) &= 0 \\
M_y(N_3) &= 0 \\
M_y(N_4) &= N_{4z}a\sin 60^\circ \\
M_y(N_5) &= N_{5z}a\sin 60^\circ \\
M_y(N_6) &= -N_{6z}a\sin 60^\circ, \\
M_z(N_1) &= N_{1y}a\sin 60^\circ \\
M_z(N_2) &= N_{2x}a \\
M_z(N_3) &= -N_{3x}a \\
M_z(N_4) &= N_{4y}a\sin 60^\circ \\
M_z(N_5) &= -N_{5x}\frac{a}{2} - N_{5y}a\sin 60^\circ \\
M_z(N_6) &= N_{6x}\frac{a}{2} + N_{6y}a\sin 60^\circ.
\end{aligned} \tag{20}$$

Therefore, the moment of force of the sensor are

$$M_x = \sum_{i=1}^{6} M_x(N_i),$$

$$M_y = \sum_{i=1}^{6} M_y(N_i),$$

$$M_z = \sum_{i=1}^{6} M_z(N_i). \tag{21}$$

3. STRUCTURE OF THE SENSOR

A newly designed sensor based on our proposed model is constructed, which is shown in Photo. 1. There are 6 legs in this sensor. The elastic sensing elements of the sensor are made from 6 brazen pipes with thickness of 0.1mm and diameter of 3 mm. A ball joint unit is assembled by a rod end bearing and two knuckle joints as shown in Fig.6. This design make the centerlines of the two pipe can cross at the center of the ball. This structure allow the upper plate and lower plate can turned slightly in any directions arround the balls.This is a feature in this design. This kind of joint can effectively reduce torsion and bending of the pipes when a external load acted on the sensor. In other words, It can effectively reduce interference among F_x, F_y, F_z, M_x, M_y and M_z. The knuckel joints and the body of the rod end bearings are made of aluminum alloy in order to reduce weight.

In the situation of all joints are fixed and the legs and joints are made of one metal plate[5], some legs, actually are beams, not only were tensed or compressed, but also were bend and twisted a little when a force acted on the sensor. The bending and twisting also contributes some strains to guages, This is one of main source of error. In addition, the sensing element of this kind of sensors are beams with thickness 0.2~0.3 mm, The flexual rigidity and torsional rigidity of the beam are weak. However, on the condition of same cross section and same material, the flexual rigidity and torsional rigidity of pipe are far stronger than that of beam, yet sensibility in normal stree is same. This is why beams was replace by pipes.

Photo. 1 Structure of the sensor

4.THE RESULT OF TEST AND ERROR ANAL SIS

Photo.2 The device of measurement

In order to investigate the validity of the proposed method, Performance of the new sensor is tested. A spring balancer is used to apply force to the finger in our experiment as shown in Photo.2. The accuracy of the balancer is0.01*N* and the maximum scale is 10*N*. The input-output relation of average is shown in Fig. 7

To the sensor which elastic elements are beams and joints are rigid joints[5], its input-output relation is shown in Fig.8. It is shows that the performance of the new sensor is better than that of the sensor with beam.

It can be found that there is a roughly linear relation,

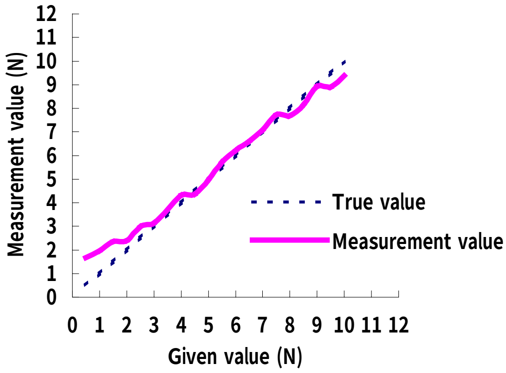

Fig.7 Input-output relation of the sensor in new structure

between 2.00 and 9.00N in Fig.7. The results shows measurable range of the sensor is from 2.00*N* to 9.00*N* and the linearity of the sensor is within 5.2% and the absolute error within 0.47*N*. Comparing with Fig.7 and Fig.8 ,The validity of the proposed method is proved. The absolute error may come from the friction between the balls and their insert. Another, the error may also come from the difference of the 6 legs in length and the difference between the real sensor and geometic model.

5. CONCLUSION

The new structure of Stewart plateform-based sensor for robot fingers is proposed. The feature of the sensor is using the new style of ball joints and the thin brazen pipe as the sensing elements. The new geometric model of six-axis

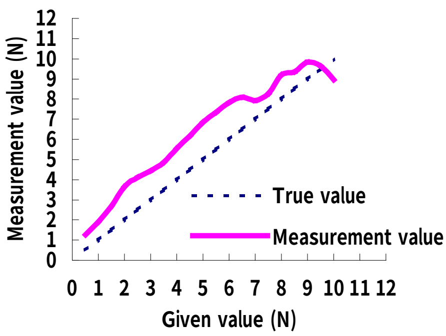

Fig.8 Input-output relation of the sensor with beams

force/moment sensor for robot finger is also proposed. When we designe the sensor, the diameter and the height of sensor can be firstly decided accoding to actual size of robot finger, then the other size of the sensor can be easily decided by the model. The grasping force and its moment and touching position can be mesured by the new sensor which has been constructed in this research.

The experiment results show that the performance of the new sensor is better than that of the sensor with beams. Concerning the linearity and rang of possibility for actual use, the new sensor are better than the sensor with beam as shown in Fig.7 and Fig 8.

The six–axis force/moment sensor is simple in this structure and manufacturing the sensor is easier than some other kinds of robot sensors. For different scale of grasping force, the cross sections of pipes can be calculated by the method developed in this paper

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REFERENCES

[1] D. Stewart, "A platform with six degree of freedo m," *Proc. Inst. Mech. Eng.* 180, pp.371-386,1965.

[2] D.R.Keer,"Analysis,Properties,and Design of Stewart-plateform transducer," *Transactions of the ASME,* Vol. 111, pp.25-28,1989.

[3] C.C.Nguyen, S.S. Antrazi,Z.L. Zhou, C.E. Campbell Jr. "Analysis and Experimentation of a Stewart Plat form-based force/torque sensor," *Int. J. Robotics Aut omat,* Vol.7,pp.133-140,1992.

[4] Chul-Goo Kang,"Closed-form Force Sensing of A 6 -axis Force Transducer Based on the Stewart Plate form," *Sensor and Actuators* A 90, pp.31-37,2001.

[5] Minghua Luo, Masanori Ito, Etsuro Shimizu and Feifei Zhang, "Development of a Six-axis Force/Tac tile Sensor for Robot Finger by Employing Spring Beams,"*Proc. of the 29th Annual Conference of the IEEE industrial Electronics Society,* pp.1505-1510, 2003

[6] J.L.Meriam, "Mechanics," second edition, pp.14-25, 1961.

[7] Stephen. P. Timoshenko and James M. Gere, "Mech anics of Materials" pp.6-16,1972.

[8] Giyou Haku Takahashi and Susumu Machida, "Foun dation of Machanics of Materias," pp.2-20,1980.

[9] Xin-Jun Liu, Jinsong Wang, Feng Gao, and Li-Ping Wang, "On the Analysis of a New Spatial Three-D egree-of-freedom Parallel Manipulator," *IEEE Transa ctions on Robotics and Automation,* Vol.17,No.6,pp9 59-968, 2001.

[10] Nobuharu Mimura, Daiho Yokoyama, Hajime Kato, "A Small 6 DOF Force/Tacitile Sensor for Robot Fi nger Applying Parallel Mechanism" *The Science Le cture of Journal of Robot Society of Japan*,1996.

[11] J. Kenneth Salisbury, Jr. "Interpretation of Contact Geometries from Force Measurements," *ISSR,* Chapt er 6, pp.565-577,1984.

[12] Guangjunliu, Kar Iagnemma, Steven Dubowsky, Gui llaume Morel, "A Base Force/Torque Sensor Approa ch to Robot Manipulator Inertial Parameter Estimati on," Proc. of *IEEE International Conference on Ro botics Automation,* pp.3311-3321, 1998.

[13] Toru Omata, "Dexterous Hand," *Journal of the robo tics Society of Japan* Vol.18,No.6,pp.760-762,2000.

[14] Zhenlin Jin Feng Gao and Xinjun Liu, "Novel ecou pled and isotropic 6-axis force/torquer robot sensor," *Journal of Transducer Technology,* Vol.19, No.4, p p.26-28, 2000.

[15] Sheng A. Liu, Hung L.Tzo,"A novelsix-component force sensor of good measurement isotropy and sen sitivities," *Sensor and Actuators A* Vol. 100, pp223-230, 2002.