Distributive Behavior-based Control for a Flexible Conveying System

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Abstract
This paper presents a control strategy for a proposed flexible conveying system (FCS) which consists of multiple arrays of cells. Each wheel of cell is driven by a two degree-of-freedom mechanism. The FCS can handle multiple objects independently and simultaneously. The position and direction of a targeted object are directly controlled based on the summation of driving force and moment from the supporting cells. Importantly, the behavior-based control with subsumption architecture is applied to control the direction of driving force of supporting cells and to manipulate an object towards its desired position. The collision avoidance among objects is also implemented under the behavior-based control. Finally, the dynamical simulation of the proposed system is used to illustrate its system performance.

1. Introduction

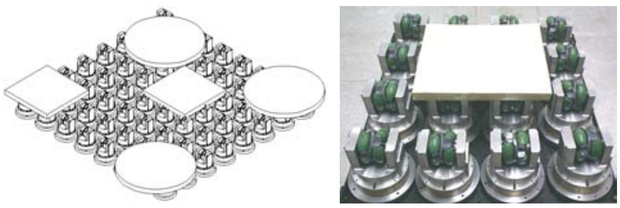
In the flexible manufacturing systems (FMS), many product parts with different production plans are required to share the same production line. The parts are conveyed among several machines in arbitrary orders. Hence, the conveyor that can handle multiple parts independently and simultaneously is needed in the production line. Traditionally, every object is moved by its own transportation system e.g., a pick-and-place robot. With an increasing number of objects to be moved simultaneously, this solution eventually becomes unfavorable due to end effector's conflict and high cost.

Recently, several attempts have been made to propose new conveyors that allow a controlled motion of multiple objects on individual trajectory. S. Konishi and H. Fujita proposed small parts conveying system using fluidic micro actuators without feedback sensor [1]. A positioning method allows every actuator to exert forces to obtain desirable directions. K. Bohringer, Donald, and MacDonald have applied the array of actuators into the microscopic scale [2]. Their actuators consist of asymmetric torsional resonators that can lift objects lying on top of the actuator while applying horizontal forces to create motion. Luntz, Messner, and Choset have built arrays of cell for moving parcels with three degree-of-freedom i.e., two translations and one rotation [3][4]. Their mechanical configuration consists of actuator cells having a pair of orthogonally oriented roller wheel. Those cells are capable of producing a force perpendicular to the wheel axis while allowing free motion in parallel to the wheel axis. Each of cells also contains a sensor that can detect the presence of parcel. P.U. Frei, M. Wiesendanger, R. Buchi, and L. Ruf proposed a vibratory conveyor that is normally used to move things like powder or gravel [5]. They applied the combination of horizontal and vertical oscillations to produce a non-zero resulting friction force. The objects can be moved along any horizontal direction with this friction force. T. Fukuda, K. Sekiyama, I. Takagawa, S. Shibata, and H. Yamamoto proposed a flexible transfer system, which composed of autonomous robotics modules [6][7]. Normally, this system is used to transfer a palette carrying object parts. They also applied the hybridization method between the distributed and centralized approaches to control this system.

In this research, a flexible conveying system (FCS), which consists of multiple arrays of cells, is proposed. Each cell is a wheel driven by a two degree-of-freedom mechanism i.e., spinning and steering. The FCS has several advantages over conveyor belts and conventional robot manipulators. It provides simultaneous transportation of multiple objects on individual trajectory. These include feeding, orientating, sorting, separating, and arranging objects. Furthermore, a distributive behavior-based control is presented to manipulate multiple objects toward their desired position without any collision among them.

2. Flexible Conveying System (FCS)

In this paper, a flexible conveying system (FCS), which consists of multiple arrays of cells, is presented. Each cell is a wheel driven by a two degree-of-freedom mechanism for spinning and steering. The roller wheel provides the powered motion perpendicularly to its axis of rotation while allowing free motion in parallel to its axis of rotation. Figure 1 shows the structure of FCS and its prototype, which is designed and fabricated at FIBO.



(a) (b)

Figure 1 (a) Structure of Flexible Conveying System
(b) Prototype of Flexible Conveying System

In the FCS, a distributive behavior-based control is applied. Each cell has its own controller for low-level control. The tasks of this controller include wheel-speed controlling, power and motor drive controlling, object sensing, and communicating with its host and its four neighboring cells. The arrays of cell are designed to be easily snapped together. Furthermore, they can be reconfigured to meet the demands in a flexible manufacturing environment. The redundancy of cell arrays also allows for good fault tolerance because targeted objects can be redirected around or passed over broken cells.

3. Distributive Behavior-based Control

To control the proposed FCS, the behavior-based control with subsumption architecture is suitably applied [8][9][10]. Generally, the FCS needs to manipulate multiple objects toward to their desired positions without any collision among them. The host PC assigns the desired position and direction of object to each cell.

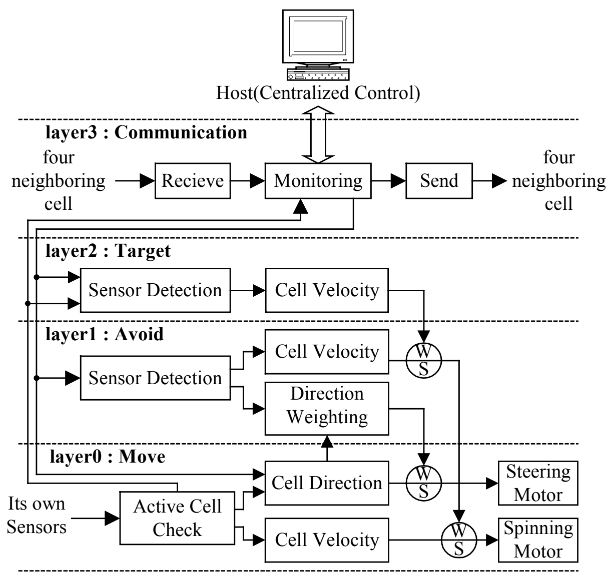


Figure 2 Four-layer control of subsumption architecture

The structure of a subsumption architecture, which consists of four layers, is presented in Figure 2. Each layer works on individual goal concurrently and asynchronously. The response of a lower layer can be suppressed by a higher layer's one.

3.1 Layer 0: Move

This layer is the lowest layer. It always accelerates the spinning roller wheel (Vc_0) when it is stimulated from its own sensor signals as equation (1).

$$Vc_0 = Wv_0 \cdot V\,max_0 \qquad (1)$$

$$Wv_0 = 1 - e^{-\alpha_{v0} I_0} \qquad (2)$$

where Wv_0 is a velocity weight of each layer 0. α_{v0} is a coefficient that adjusts the velocity response function of layer 0. I_0 is a distance between the cell's location and the object's starting location and $Vmax_0$ is the maximum velocity of this layer. This layer also manipulates the steering roller wheel (θc_0) upon the equation (3).

$$\theta c_0 = a\tan\left(\frac{g_y - s_y}{g_x - s_x}\right) \qquad (3)$$

where g_x and g_y are the goal positions in x-axis and y-axis, respectively. s_x and s_y are the starting positions in x-axis and y-axis, respectively.

3.2 Layer 1: Avoid

This layer reduces the speed of the spinning roller wheel (Vc_1) when it is stimulated from neighboring cells' sensor signals as equation (4).

$$Vc_1 = Wv_1 \cdot V\,max_1 \qquad (4)$$

$$Wv_1 = 1 - e^{-\alpha_{v1} I_1} \qquad (5)$$

where Wv_1 is a velocity weight of each layer 1. α_{v1} is a coefficient that adjusts the velocity response function of layer1. I_1 is the shortest distance between the cell's location and the approximated locations of the other objects. $Vmax_1$ is the maximum velocity of this layer. This layer also turns the steering roller wheel (θc_1) away from obstacles, depending upon the data obtained from the sensors of four neighboring cells as equation (4).

$$\theta c_1 = \theta c_0 \pm 180 \cdot Wd \qquad (4)$$

$$Wd = e^{-\alpha_d I_1} \qquad (6)$$

where Wd is a direction weight of each layer 1. α_d is an adjustable coefficient for changing a steering roller wheel angle. Criteria for setting the steering roller wheel angle can be presented in Figure 3.

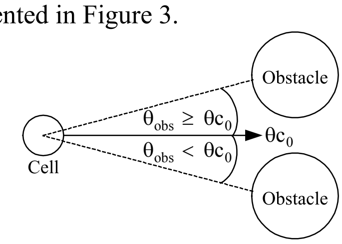


Figure 3 Criteria for setting the steering roller wheel angle

As seen in Figure 3, a steering roller wheel angle is initially set according to the response of the layer 0. If the measured obstacle angle (θ_{obs}) is larger than the predefined steering roller wheel angle, the steering roller wheel angle will be increased as described in equation (4). Decreasing the steering roller wheel angle will be done if the smaller obstacle angle is sensed.

3.3 Layer 2: Target

This layer is responsible for decelerating the spinning roller wheel when the object approaches the desired position as equation (5).

$$Vc_2 = Wv_2 \cdot V\,max_2 \qquad (5)$$

$$Wv_2 = 1 - e^{-\alpha_{v2} I_2} \qquad (6)$$

where Wv_2 is a velocity weight of layer 2. α_{v2} is a coefficient that adjusts the velocity response function of layer 2. I_2 is a distance between the cell's location and the object's goal location and $Vmax_0$ is the maximum velocity of this layer.

3.4 Layer 3: Communication

This layer is the highest layer, which receives and sends data from/to its four neighboring cells, and sends signal to host PC when its own controller fails. The data has the pattern defined as following: ID, data type, and data arrays. Once the ID is matched, the cell receives and stores the data into its buffer.

3.5 Velocity Response Function

The responses of layer 0, layer 1, and layer 2 that control the spinning roller wheel depend on the velocity weight (Wv_i). In the layer 0, if the velocity weight is big, the response of controlling the spinning roller wheel will be fast. For layer 1 and layer 2, if the velocity weight is small, the response of controlling the spinning roller wheel will be fast. Figure 4 shows plot of velocity weights versus distances I with α_{vi} ranging from 0.001 to 0.01.

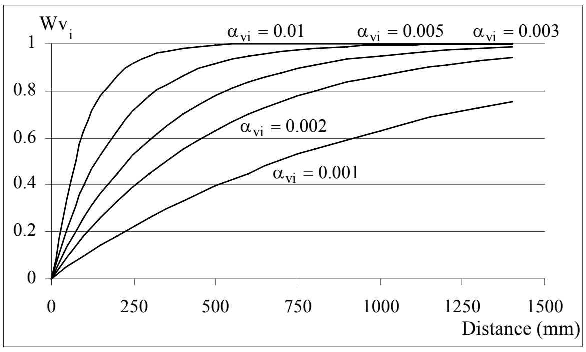


Figure 4 The velocity weights are varied with α_v

3.6 Direction Response Function

The responses of direction weighting module that control the steering roller wheel depend on direction weight (Wd). If the direction weight is small, the response of controlling the steering roller wheel, that is for obstacle avoidance, will be fast. Figure 5 shows plot of direction weights versus distances I with α_d ranging from 0.001 to 0.01.

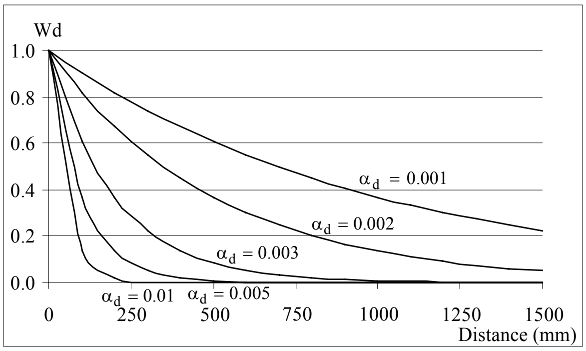


Figure 5 The direction weights are varied with α_d

3.7 Suppressor Algorithm

A higher layer can suppress the velocity response of a lower layer as shown in Figure 5.

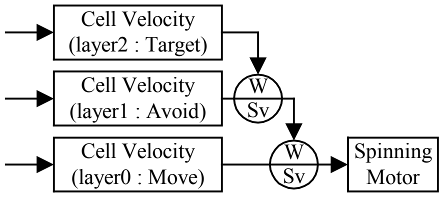


Figure 5 Diagram for subsumption-based control for the spinning roller wheel

Criteria for setting the steering roller wheel angle can be describe as equation (7).

$$Vc = \begin{cases} Vc_2 & if \quad Wv_2 \leq Sv_1 \\ Vc_1 & if \quad Wv_1 \leq Sv_0 \\ Vc_0 & otherwise \end{cases} \tag{7}$$

where Sv_1 is a threshold of layer 2 which is used to suppress the response of layer 1. Sv_0 is a threshold of layer 1 which is used to suppress the response of layer 0. The layer 1 can also suppress the direction response of layer 0 as shown in Figure 6.

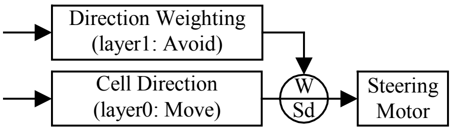


Figure 6 Diagram for subsumption-based control for the steering roller wheel

Criteria for setting the steering roller wheel angle can be describe as equation (7).

$$\theta c = \begin{cases} \theta c_1 & if \quad Wd \leq Sd \\ \theta c_0 & otherwise \end{cases} \tag{8}$$

4. Simulation Results

Figure 7 illustrates a GUI-based simulator using the proposed control strategy, which can handle multiple objects independently and simultaneously. This simulator has been developed under the Windows-based operating system using the Microsoft Visual C++.

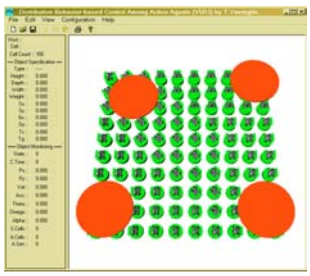
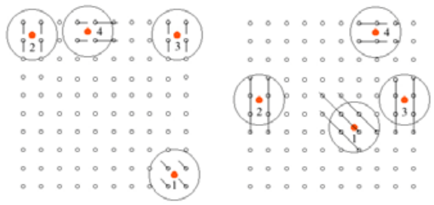
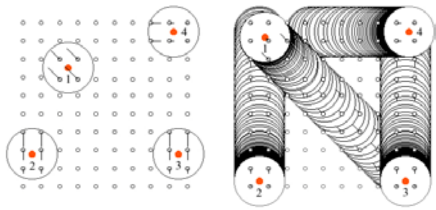


Figure 7 GUI-based simulator of FCS

There are two experimental sets which are manipulations of multiple objects with/without collision avoidance. In the first experiment, the simulation was run using the parameters of $\alpha_{v0} = 0.005$, $\alpha_{v2} = 0.02$, $S_{v1} = 0.7$, weight of each object is equal to 1 kg, and the maximum velocity of each layer is 10 cm/sec.

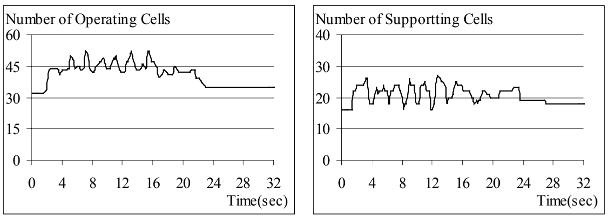


time = 0.2 sec time = 8.8 sec



time = 16.2 sec time = 32 sec

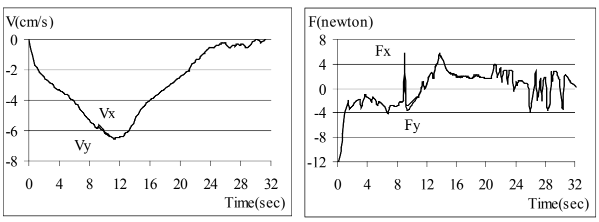
Figure 8 The status of FCS which indicates the directions of driving forces of supporting cells and the locations of objects



(a) (b)

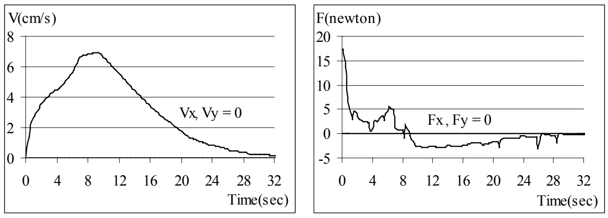
Figure 9 (a) Number of operating cells (b) Number of supporting cells under a subsumption architecture during operation

Figure 9 (a) shows the number of operating cells, which are dynamically activated to guide the object's direction. Figure 9 (b) shows the number of supporting cells, which applied the driving force to control the object's velocity and direction to the desired location. The directions of driving forces of supporting cells, which are applied to each object, are presented in Figure 8. Each path of object is regulated to be a straight line path from the starting position to the goal position.



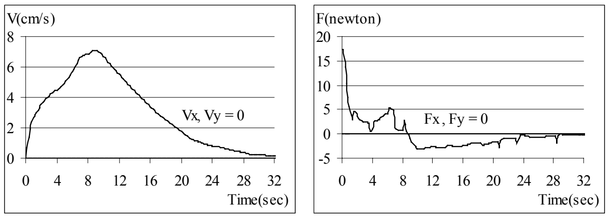
(a) (b)

Figure 10 (a) Velocity profiles of an object1 (b) Driving force of an object1



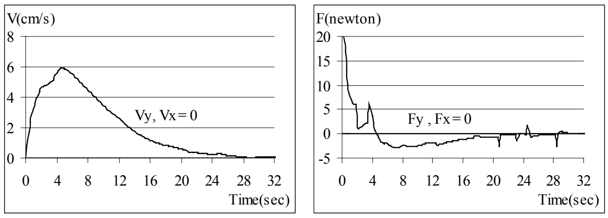
(a) (b)

Figure 11 (a) Velocity profiles of an object2 (b) Driving force of an object2



(a) (b)

Figure 12 (a) Velocity profiles of an objects3 (b) Driving force of an object3

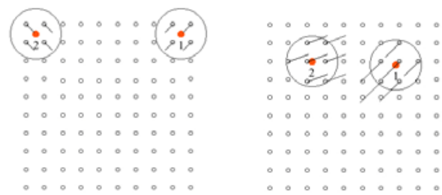


(a) (b)

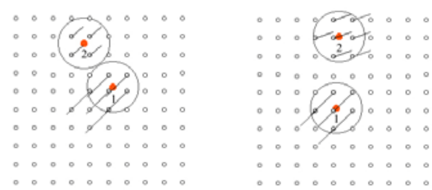
Figure 13 (a) Velocity profiles of an object4 (b) Driving force of an object4

Figure 10(a) - Figure 13(a) illustrate that the velocity of each object is greatly increased after the object starts moving. Subsequently, its velocity is decreased when the object approaches the desired position. In addition, the driving force of each object is shown in Figure 10(b) - Figure 13(b).

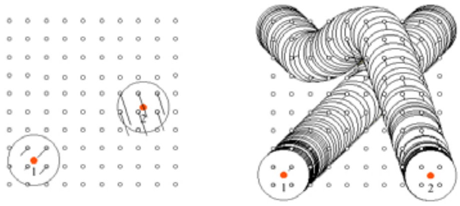
In the second experiment, the simulation was run using the parameters of $\alpha_{v0} = 0.005$, $\alpha_{v1} = 0.02$, $\alpha_{v2} = 0.02$, $\alpha_d = 0.02$, $S_{v0} = 0.7$, $S_{v1} = 0.7$, weight of each object is equal to 1 kg, and the maximum velocity of each layer is 10 cm/sec.



time = 0.2 sec time = 3.2 sec



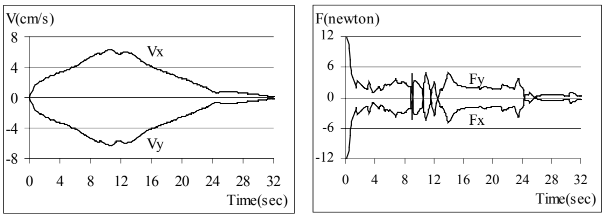
time = 8.6 sec time = 10.6 sec



time = 20 sec time = 35 sec

Figure 14 Collision avoidance between two objects in the FCS

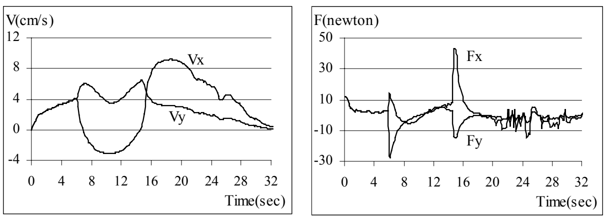
Figure 14 illustrates that the FCS with the subsumption architecture can handle a collision between two targeted objects. Both objects start moving towards their destinations simultaneously. Since the object1 approaches the area of intersection before another one, the object2 is requested to change its path to avoid collision. After the potential collision is free, the object2 moves back to its original path. Finally, both objects can reach their destinations without any collision.



(a) (b)

Figure 15 (a) Velocity profiles of an objects1 (b) Driving force of an objects1

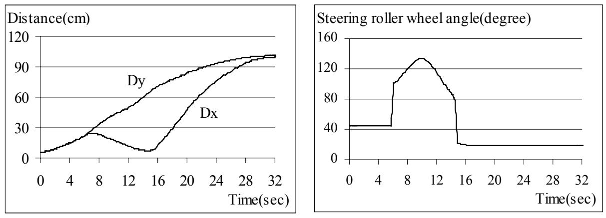
Figure 15 (a) illustrate that the velocities of an object1 in x-y axis, which manipulate an object1 towards the destination. In addition, the driving force is greatly increased after the object starts moving. Subsequently, its driving force is decreased when the object approaches the desired position.



(a) (b)

Figure 16 (a) Velocity profiles of an objects2 (b) Driving force of an objects2

Figure 16 illustrate that the velocities of an object 2 in x-y axis are decreased when the object2 approaches the object1. After the potential collision is free, the object velocities of object2 in x-y axis is greatly increased and decreased when the object2 approaches the desired position. The object2 avoids a collision with the object1 in x-direction as shown in Figure 17(a). Figure 17(b) illustrates that the steering roller wheel angle is increased when the object approaches the object1.



(a) (b)

Figure 17 (a) Positions of an objects2 vs. time (b) Steering roller wheel angle of an objects2 vs. time

5. Conclusions

This paper presented a flexible conveying system (FCS) and its control strategy for manipulating multiple objects independently and simultaneously. The behavior-based control under subsumption architecture is applied to control the direction of force of supporting cells and to manipulate multiple objects towards their desired positions. The collision avoidance among objects is also implemented. Finally, a GUI-based simulator of FCS is constructed to illustrate the system performance.

6. Acknowledgement

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References

[1] S. Konishi and H. Fujita, “Two – dimensional Conveyance System Using Cooperative Motions of Many Microactuators”, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 1996.

[2] K. Bohringer, B. Donald, R. Mihailovich, and N. Mac Donald, “A theory of manipulation and control for microfabricated actuator arrays”, Proceedings. IEEE International Conference on Robotics and Automation, 1994.

[3] J.E. Luntz and W. Messner, “A Distributed Control System for flexible material Handing”, IEEE Control System Magazine, February 1997.

[4] J.E. Luntz, W. Messner, H. Choset, “Distributed Manipulation Using Discrete Actuator Arrays”, The International Journal of Robotics Research, 2001, Vol. 20, No. 7, pp. 553-583.

[5] P.U. Frei, M. Wiesendanger, R. Buchi, and L. Ruf. “Simultaneous planar transport of multi object on individual trajectories using friction forces”, Proceedings of the Workshop on Distributed Manipulation at the International Conference on Robotics and Automation, 1999.

[6] T. Fukuda, K. Sekiyama, I. Takagawa, S. Shibata, and H. Yamamoto, “Hybrid Approach of Genetic Algorithms and Learning Automata for Flexible Transfer System”, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 1999.

[7] T. Fukuda, I. Takagawa, "Design and Control of Flexible Transfer System", Intelligent Control and Automation, Proceedings of the 3rd World Congress on Intelligent Control and Automation, 2000, Vol. 5, pp. 3049 –3054.
[8] R.A. Brooks, "A Robust Layered Control System for a Mobile Robot", MIT AI Memo 864, September 1985.
[9] R.C. Arkin, "Behavior-Based Robotics", The MIT Press: Cambridge, Massachusetts, 1998.
[10] T. Yaemglin and S. Charoenseang, "A Flexible Conveying System using Hybrid Control under Distributed Network", Proceedings of the 17th International Technical Conference On Circuits/Systems Computers and Communications, Phuket, Thailand, July 2002.