MVA'94 IAPR Workshop on Machine Vision Applications Dec. 13-15, 1994, Kawasaki

MOVEMENT TRACER SYSTEM USING NON-PARALLEL MULTIPLE LINE DETECTORS AND HIGH ORDER CORRELATION ANALYSIS

Masashi Sakamoto, Keisuke Kameyama, Katsuyuki Kuwano, and Takuso Sato
Interdisciplinary Graduate School of Science and Engineering
Tokyo Institute of Technology, Japan

4259 Nagatsuta-chou, Midori-ku, Yokohama 226, JAPAN

ABSTRACT

A novel object movement tracer using high order correlation analysis of optical detector array signals is introduced. The optical detectors are arranged non-parallel and the movement loci is estimated by a set of detected signal delays and geometrical position of the detectors. This system is applicable to general robotic movement detection because: 1) It employs a non-contact measurement method, 2) The system can be made very compact, and 3) It enables to approximate the movement loci with arcs. In this work, at first, we have looked into estimation of the locus by using a turntable and detecting the surface pattern to evaluate the accuracy of the locus estimation. Secondly, the detector was mounted on an autonomous vehicle to estimate its running trace by detecting the ground pattern. Further, we will introduced a new detector array using optical fibers which enables a much flexible arrangement with the optical detector array.

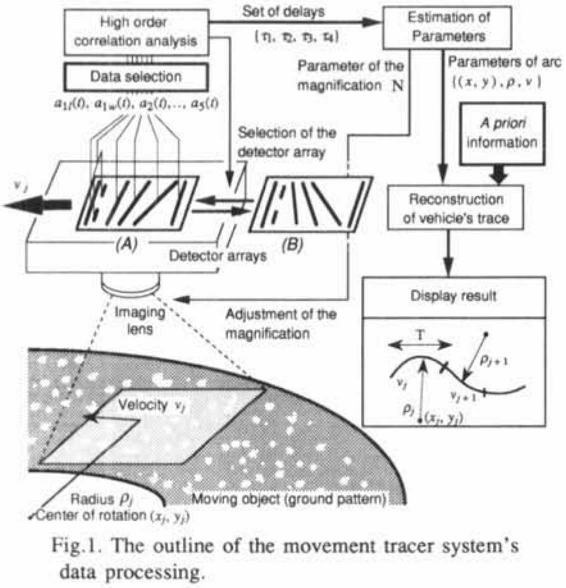


Fig.1. The outline of the movement tracer system's data processing.

1. INTRODUCTION

Movement trace detection is essential for vehicular navigation systems and autonomous motion controlling systems for robots and unmanned cars. The general trend of such detection methods is to detect the velocity and the movement direction periodically, and to reconstruct the locus of the object as a broken line. Among contact measurement methods, there are combinations of tachometer for velocity measurement, and steering angle encoder for running direction detection. For the non-contact methods, correlation method and gyros have been jointly used, for velocity and angle detection. Both of these methods share a same disadvantage that, in order to improve accuracy, time period of data acquirement must be reduced. Also, it is necessary to combine several measurement devices for velocity and angle detection for they are measured using different means.

In this work, the conventional method to compute second order correlation of the running pattern of the ground to measure velocity is extended to obtain information on the curve traces simultaneously. In Fig. 1, the scheme of trace estimation is shown. Five optical detectors are used to monitor the ground pattern and fifth order correlation analysis is used to estimate the set of delays between the detected signals. Each trace section of the vehicle is approximated as an arc, of which center coordinate, radius and velocity are estimated with use of the signal delay set and geometrical positioning of the optical detectors. In section 2, the principle of arc estimation is described. In section 3, three methods for accurate trace estimation are introduced. In section 4, the experimental setup and results are shown.

2. PRINCIPLE OF TRACE ESTIMATION[1][2][3]

Our method of trace estimation tries to approximate the vehicle's movement during a short time period as an arc; it is assumed that the trace is an arc of fixed center and constant radius with stable velocity during each detection period. We will attempt to estimate the parameter set from the intensity variation of the running ground pattern projected onto the detector array. The geometry of the detector array is shown in Fig. 2. Six detectors are placed so that detectors D_{1l}, D_{1w} and D_5 will be parallel, and the other detectors are slanted with unique angles against the base axis x. Although detector D_{1w} is physically identical with the other detectors, the surface is masked so that only light passing through the two small windows will be detected. Detector D_{1l} is used only when a very bright point is included in the detected intensity, whereas D_{1w} is used in usual cases. Another detectors (D_2, D_3, D_4, D_5) are used both cases, so the number of detectors used for an arc estimation is always five. The conditions of detector selection will be discussed in the next section.

The output signal of each detector ($i = 1l, 1w, 2, ..., 5$) is

$$a_i(t) = \int_{l_i} \zeta_i(x, t)\, dx \tag{1}$$

where $\zeta_i(l_i, t)$ $(i = 1l, 1w, 2, ..., 5)$ is the varying component of the light intensity detected at position x at time t, and li is the length of the detector.

When computing the correlation of $a_i(t)$, the signal from the selected detector among D_{1l} and D_{1w} will be $a_1(t)$. The set of detection time lag between the first detector and the others can be estimated using the fifth order momentum function

$$m_5(\tau_1, \tau_2, \tau_3, \tau_4) = \frac{1}{T}\int_0^T a_1(t)a_2(t+\tau_1)a_3(t+\tau_2)a_4(t+\tau_3)a_5(t+\tau_4)\, dt \tag{2}$$

assuming that the detected pattern is random with a delta-like fifth order autocorrelation. Then m_5 will have a unique peak in the momentum space at the

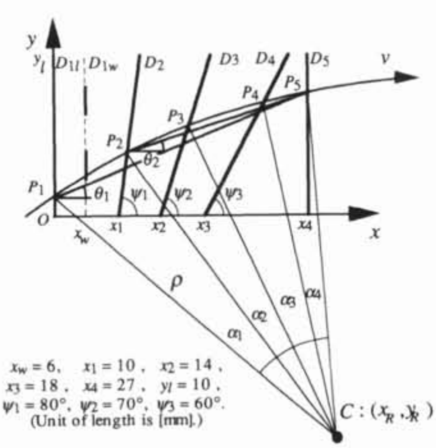


Fig.2. Geometry of the detector array. Embedded optical detectors are $D1l, D1w, ..., D5$ and output signals of them are $a1l(t), a1w(t), ..., a5(t)$.

necessary coordinate of delays (τ_1, τ_2, τ_3, τ_4). Using the set of delays and the dimensionalities of the detectors, para-meter set (v_R, ρ_R, x_R, y_R) which determines the arc trace is calculated as follows.

If the points P_i, angles α_i, θ_1 and θ_2 are defined as drawn in Fig. 2, it can be written using τ_i, α_i, ρ_i (signed : positive for right turns) and v as

$$\frac{\rho\alpha_1}{V} = \tau_1 \tag{3}$$

$$\frac{\alpha_1}{\alpha_s} = \frac{\tau_1}{\tau_4} \tag{4}$$

$$\frac{\alpha_2}{\alpha_s} = \frac{\tau_2 - \tau_1}{\tau_4} \tag{5}$$

$$\frac{\alpha_3}{\alpha_s} = \frac{\tau_3 - \tau_1}{\tau_4} \tag{6}$$

where $\alpha_s = \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$.

Parameters (v, ρ, x_R, y_R) can be calculated using (3) ~ (6) and the coordinates of the detectors as

$$\rho = \frac{x_4}{2\cos\theta_1 \sin\left(\frac{\tau_4}{\tau_1}\Omega\right)} \tag{7}$$

$$v = \frac{2\rho\Omega}{\tau_1} \tag{8}$$

$$x_R = \frac{1}{2}\left\{ x_4 + \mathrm{sgn}(\rho)\tan\theta_1 \sqrt{(2\rho\cos\theta_1)^2 - x_4^2} \right\} \tag{9}$$

$$y_R = y_1 + \frac{1}{2}\left\{ x_4 \tan\theta_1 - \mathrm{sgn}(\rho)\sqrt{(2\rho\cos\theta_1)^2 - x_4^2} \right\} \tag{10}$$

Parameter y_l which is the y-coordinate of P_l is

$$y_1 = y_3 + \left(x_4 - x_1 - \frac{y_3}{\tan\psi_1} \right)\tan(\theta_1 - \Omega) - x_4\tan\theta_1 \tag{11}$$

where

$$y_3 = \left\{ x_4 + 2\rho\cos(\theta_1 - \Omega)\sin\left(\frac{\tau_1 - \tau_4}{\tau_1}\Omega\right) - x_1 \right\}\tan\psi_1 \tag{12}$$

and

$$\Omega = \theta_1 - \theta_2 . \tag{13}$$

Substituting α_i ($i = 1, ..., 4$) expressed with parameters θ_1, Ω, ρ and y_1 into (5) and (6), and using $\Omega = 2\alpha$, two equations (14) and (15) with parameters θ_1 and Ω are obtained.

$$\sin(y_2 + c_1 W) - Z_1 = \tan\theta_1 \left\{ \cos(\psi_2 + c_1\Omega) + Z_2 \right\} \tag{14}$$

$$\sin(\psi_3 + c_2\Omega) - Z_3 = \tan\theta_1 \left\{ \cos(\psi_3 + c_2\Omega) + Z_4 \right\} \tag{15}$$

Here, $c_1 = (\tau_1 + \tau_2 - \tau_4)/\tau_1$ and $c_2 = (\tau_2 + \tau_3 - \tau_4)/\tau_1$. Z_1, Z_2, Z_3 and Z_4 are functions of Ω, however, they will be omitted here. Eliminating θ_1 from (14) and (15), an equation

$$\sin\left\{ \psi_2 - \psi_3 + (c_1 - c_2)\Omega \right\} + Z_4 \sin(\psi_2 + c_1\Omega) + Z_3\cos(\psi_2 + c_1\Omega) - Z_2\sin(\psi_3 + c_2\Omega) - Z_1\cos(\psi_3 + c_2\Omega) - Z_1 Z_4 + Z_2 Z_3 = 0 \tag{16}$$

is derived, from which Ω is obtained numerically. Using the derived Ω, θ_1 is calculated from (14) or (15). Substituting Ω and θ_1 into equations (7) ~ (10), the set of necessary parameters (v, ρ, x_R, y_R) is obtained. The actual trace is obtained by transforming the parameters to the movement of the vehicle center (x_0, y_0). Furthermore, the para-meters transformed to the ground coordinate by using the magnification factor of the imaging lens. Finally, with conversion of (local) detector coordinate of each successive arc to the ground coordinate, the whole trace is estimated.

3. THREE METHODS FOR ACCURATE TRACE ESTIMATION

3.1 Adaptive Data Selection According to the Texture of the Ground Pattern

In order to eliminate the positional ambiguity of the estimated arc, the detector with narrow sindows is used. However, when a particular point on the ground which is significantly brighter than the background was detected as signals with a spike by detectors (D_{1l} and other detectors except D_{1w}), it would enable a much accurate estimation. The condition of detector selection is as follows. When the detected signals satisfy a condition

$$a_{1l}(t) > \gamma\sigma_{1l}, \tag{17}$$

detector D_{1l} will be used for arc estimation, otherwise detector D_{1w} will be used. By computer simulation, we determined the parameter as $\gamma = 5$.

3.2 Alternative Selection of Detector Array and Optimization of Measurement Condition Using Initial Estimation

To obtain accurate traces, an optimal illmination, suitable detector array arrangement and the magnification of optimal system are chozen adaptively. At first, the illumination is regulated so as to emphasize the reflected light. Secondly, two detector arrays A and B having their photosensors aligned in symmetry are prepared (see Fig. 1.), and the detector which gives an arc estimation with a positive radius, *i.e.* $\rho > 0$, is used for it yields a relatively accurate arc estimation due to the geometrical positioning of the sensors. The sign of radius (turn of the trace) is determined by comparing each array's delay time τ_{1A}, τ_{1B} and the detector with larger τ_1 is selected. Further, an accuracy of arc estimation depends on the arc's size projected onto the detector array, so it is necessary to optimaize the magnification. To obtain an accurate arc estimation, the magnification is adjusted to satisfy the relation

$$N = \frac{\frac{w}{m}}{2 \times |\rho|} \rightarrow 1\,. \tag{18}$$

(N: the parameter of magnification, m: magnification,

ρ: radius of an arc, w: width of the sensor array)

Finally, under the optimal conditions explained above, the movement is measured again.

3.3 Trace Reconstruction with use of *A Priori* Knowledge

After each partial trace is approximated with an arc, they are joined to make one long trace. In this operation, some *a priori* knowledge is utilized to reduce computation and to improve estimation accuracy and efficiency. The three heuristics used in the system are listed in the following.

a) When the estimated arc has inappropriate parameters, *e.g.* $|\rho_j| > |\rho_{min}|$ or $v_j > v_{max}$ where ρ_{min} and v_{max} are determined by the experimental setup, this arc section of the trace estimation is rejected and the section of the trace will be extrapolated with the adjancent arcs.

b) To improve the quality of the correlation function by using more data points, detected signals of adjacent trace sections that are estimated to be of similar velocity and radius will be joined, and the trace of multiple section will be estimated as a single arc.

c) Obtaining a coordinate information from other sources, the whole trace may be corrected.

4. EXPERIMENTS

4.1 SETUP

The experimental setup and the data flow is depicted in Fig. 6. The optical detector array was set at the imaging plane of a 35[mm] camera with zoom lens. The detected signals were amplified and unnecessary components (50[Hz] and high frequency components) were eliminated and sampled with a 12-bit A/D comverter. The correlation analysis was processed in a computer (NEC PC-9801) using a vector signal processor (Canopus ZR34161). The estimated result of the arc trace was displayed on the CRT. As a moving object, a turntable painted matt-black was used for single arc estimation. For several sections of arc estimation, the remote-controlled vehicle on a matt-black surfaced board was used. In both cases, white paper pieces (diameter~6[mm]) were used as the ground pattern. The overall time for estimation was about 3[s] for a ground pattern sampled with 2048 points per detector.

4.2 EXPERIMENTAL RESULTS

The result of trace estimation for single arc is shown in Fig. 4. Selecting the appropriate detector array and optimizing the magnification, more accurate trace of arc was obtained. Secondly, the result for a trace including five sections of arcs is shown in Fig. 5. A trace estimated by simple splicing of arcs varied signimicantly compared with the given one, but by using the procedure discussed in section 3.3, final estimation came very close to the given trace.

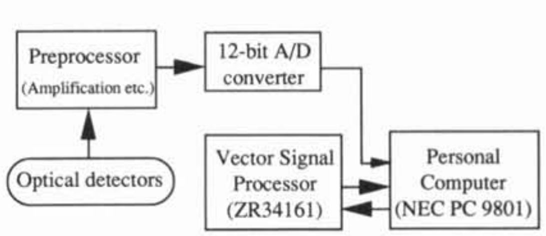
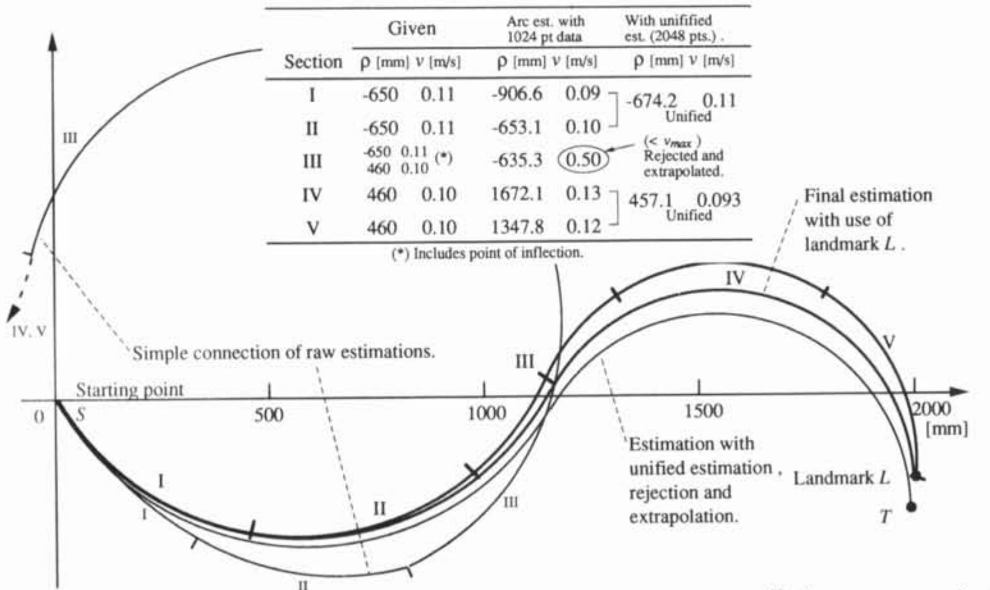


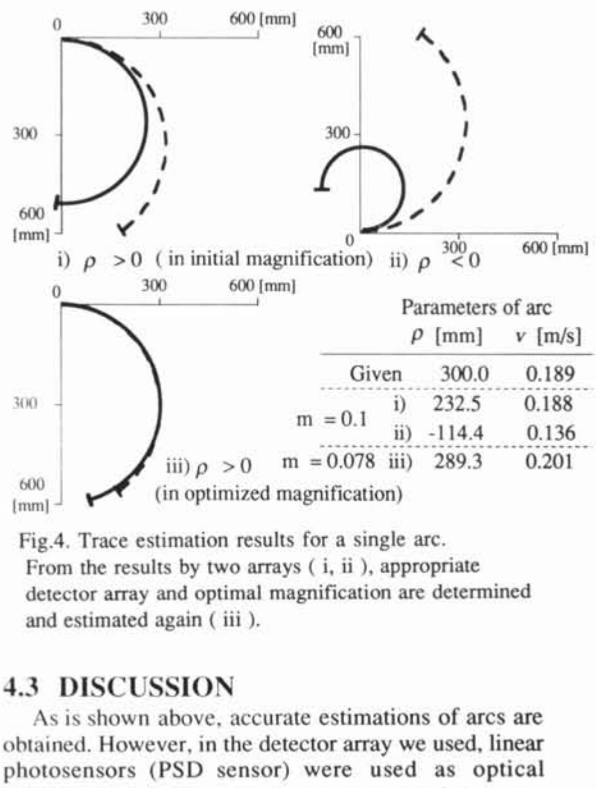
Fig.3. The experimental setup of the processing system.



Section	Given ρ [mm]	Given v [m/s]	Arc est. with 1024 pt data ρ [mm]	Arc est. with 1024 pt data v [m/s]	With unifified est. (2048 pts.). ρ [mm]	With unifified est. (2048 pts.). v [m/s]
I	-650	0.11	-906.6	0.09	-674.2	0.11 Unified
II	-650	0.11	-653.1	0.10		
III	-650 / 460	0.11 / 0.10 (*)	-635.3	0.50	(< v_{max}) Rejected and extrapolated.	
IV	460	0.10	1672.1	0.13	457.1	0.093 Unified
V	460	0.10	1347.8	0.12		

(*) Includes point of inflection.

Fig.5. Trace estimation result for a simple trace with five arcs.



Parameters of arc

		ρ [mm]	v [m/s]
Given		300.0	0.189
m = 0.1	i)	232.5	0.188
	ii)	-114.4	0.136
m = 0.078	iii)	289.3	0.201

Fig.4. Trace estimation results for a single arc.
From the results by two arrays (i, ii), appropriate detector array and optimal magnification are determined and estimated again (iii).

4.3 DISCUSSION

As is shown above, accurate estimations of arcs are obtained. However, in the detector array we used, linear photosensors (PSD sensor) were used as optical detectors, so the geometrical arrangement of detectors were limited. To solve these problems, we suggest a detector array using optical fibers. See Fig. 6. As this detector occupies less space, various geometrical arrangements of detector array is possible. For example, two sets of detector arrays in a single optical system, difference signal detection by arranging parallel line detectors adjacently, are considerable.

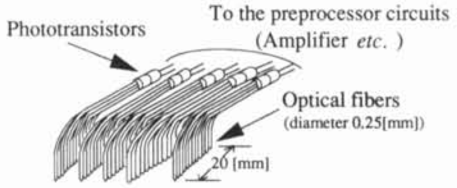


Fig.6. The detector array using optical fibers.
Instead of embedded line optical detectors, one end of the fibers are aligned in a straight line. The other end are bundled and connected to phototransistors.

5. CONCLUSION

A compact movement tracer system applicable for robot vision which uses fifth order correlation analysis of moving ground pattern was introduced. The principle of trace estimation, adaptive methods for accurate arc estimation and the heuristic methods for efficient arc splicing were described. Trace estimation experiments were done with a turntable and an experimental vehicle, and it proved that the proposed methods were beneficial in application to the movement tracer system.

REFERENCES

[1] K. Y. Jhang and T. Sato, "Flow Velocity Field Tomography Using Multiple Ultrasonic Beam Detectors and High Order Correlation Analysis", *J. Acoust. Soc. Am.*, 86-3, 1047, (1989)
[2] K. Y. Jhang and T. Sato, "3-D Velocity Field Tomography Using Multiple Plane Detectors and High Order Correlation Analysis", *Proc. Workshop on Higher-order Spectral Analysis*, pp.118-123, (1989).
[3] K. Kameyama, M. Sakamoto, H. Akagi, K. Y. Jhang and T. Sato, "Robot Vision System Using High Order Correlation Analysis", *Proc. IEEE Signal Processing Workshop on High-order Statistics*, pp. 86-90, (1993).