These isometric (constant length) tests show that as expected there is an almost linear relationship between pressure and the contractile force, with the force being dependent on the initial elongation of the system. These results agree with the theory and simulated profiles, although the forces are only 53% of their expected values. This reduction in the force output is due to system losses as described above, and is the effective force conversion factor.

The hysteretic nature of the plots is due to internal pressure differences generated in the pressurized liner/shell structure, and depend on whether the pressure cycle is increasing or decreasing (18).

Displacement/Pressure Relationship (ISOTONIC)

With the muscle unpressurized the actuator was loaded with a range of masses from 0.5kg to 5kg and the initial elongation was measured. The relationship between the elongation and the load followed the profile expected of a rubber spring system (19).

As with the isometric tests the pressure was cycled from 0kPa to 450kPa and then reduced back to 0kPa. The contractile response of the actuator during this cycle is recorded in figure 6.

The relationship between contraction and pressure is logarithmic and similar in profile to the theoretical predictions (18). As with the isometric tests the forces are lower than expected due to system losses. From these combined results the system force conversion factor is found to be 0.55. Again a hysteretic output response is obtained and as with the isometric results this is due to differences in the internal pressure during the pressure increasing and the pressure decreasing cycles.

Power/Weight Relationship

The actuator was loaded as described for the isotonic tests. Motion of the actuator was measured by a rotary position sensor connected to the A/D converter in a PC. The performance of the system was assessed using loads of 1kg, 2kg and 3kg and operating at pressures in the range 0-450kPa. A typical response profile is shown by figure 7. This damped oscillatory output response is as would be expected of a system formed from a spring/pneumatic damper arrangement. The power output for the system is shown in figure 8.

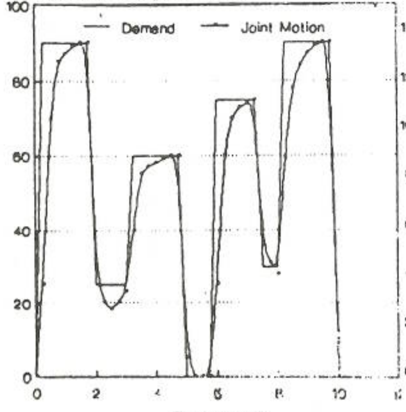

Fig.7 Response to a Pressure step Input.

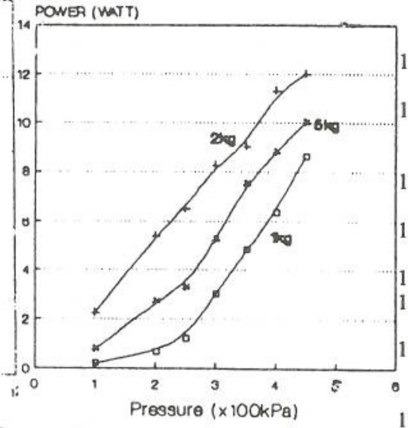

Fig.8 Power Output v Pressure

As would be expected power is closely related to the pressure and the relationship is basically linear. The power output is also dependent on the load, with the maximum power being obtained with a loading of 2kg. Under these condition the power/weight ratio of the braided muscle was 1.5kW/kg at 200kPa (2 bar) and 3kW/kg at 400 kPa.

CONCLUSIONS

For future generations of robots, especially those required to work autonomously or semi-autonomously in non-factory environments, there are many key sectors that require development, but among the most vital is the actuation system.

At present the most flexible model of a general purpose actuator is provide by human muscle which has good power/weight output combined with controlled action and robustness.

The braided muscle outlined in this report has very good power/weight (in excess of 1kw/kg at 200 kPa) and power/volume ratios. The power outputs predicted by the system model are in good agreement with the experimental results and although system losses reduce the efficiency the performance remains very impressive.

Clearly the combination of advantages of traditional pneumatic cylinders with controllable braided pneumatic muscle actuators holds considerable potential for applications in areas of robotics such as dexterous manipulator design where high power outputs are required in small volume.

REFERENCES

1. D.G. Caldwell, "Compliant Polymeric Actuators as Robotic Drive Units", Ph.d Thesis, Dept. of Electronic Eng., University of Hull, Hull, E.Yorkshire, U.K, 1990.
2. P.J. McKerrow, "Introduction to Robotics", Addison-Wesley, 1991.
3. S. Takahashi, "Piezo-electric Actuators and their Applications", J. Inst. Elect. Inf. Comm. Eng., Vol 70, no.3, pp.295-7, 1987.
4. P. Dario, M. Beramasco, L. Bernardi, and A. Bicchi, "A Shape Memory Alloy Actuating Module for Fine Manipulation", IEEE Micro-robots and Teleoperators Workshop, Hyannis, Mass. Nov.9-11, 1987.
5. Dynalloy, "Biometal Guide Book", Dynalloy Inc, Irvine, Cal., USA, 1989.
6. D. Scott, "Electro-Rheological (ER) Fluid near Commercial Stage", Automotive Eng., Vol. 93, pp75-9, Nov. 1985.
7. H. Block and J.P. Kelley, "Electro-Rheology", Journal of Physics D: Applied Physics, Vol.21, 1988, pp. 1661-77.
8. A. Katchalsky, "Rapid swelling and Deswelling of Reversible Gels of Polymeric Acids by Ionization", Experimentia, Vol.5, pp.319-320, 1949.
9. D.G. Caldwell and P.M. Taylor, "Chemically Stimulated Pseudo-Muscular Actuation", Int. J. Of Eng. Science, pp.797-808, vol. 28, no.8, 1990.
10. A. Wassermann,"Size and Shape Changes of Contractile Polymers" ed. Pergamon Press, London, 1960.
11. D.G. Caldwell, "Polymeric Gels: Pseudo Muscular Actuators and Variable Compliance Tendons", IEEE/RSJ IROS '92 Conf, pp.950-57, Raleigh, USA, 1992.
12. A. Waters, "The Magneto-elastic Effect", Williams Press, York, 1990.
13. H.S. Wolff, "Biomedical Engineering", World University Library, London, 1970.
14. Bridgestone Corp., "The Rubberuator", Product Literature, 1988.
15. R.W. Henke, "Introduction to fluid Power Circuits and Systems", Addision-Wesley, 1969.
16. F.Q. Hu, J.M. Watson, P.A. Payne & M. Page, "A Fast Opto-Pneumatic Converter for Pneumatic Actuation", IEE Colloquium on Robot Actuators", Digest 1991/146, pp. 10.1-2, 1991.
17. D.G. Caldwell, A. Razak, and M.J. Goodwin, "Braided Pneumatic Muscle Actuators", IFAC Conf. on Int. Autonomous Vehicles", Southampton, UK, April 1993.
18. ______, "The Thermodynamics Handbook", Addision-Wesley, 1970.
19. L.R.G. Treloar, "The Physics of Rubber Elasticity", Clarendon Press, Oxford, 1975.

Optical range sensors: accuracy and performance of sensors using modulated light*

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Abstract

In this paper we describe the performance and modelling of low cost optical range sensors in which the light emitted is amplitude modulated onto a radio frequency carrier. Modulation makes measurements relatively immune to ambient light levels, resulting in sensors which may be unconditionally eye safe as well as robust to environmental change. We describe and compare two methods of range measurement and present results from sensors used in the robotics programme in Oxford.

Keywords: range sensors, optoelectronic sensors, inspection, robotics

1 Introduction

Optical sensors are increasingly being used in robotics because of their high performance, especially in angular resolution and bandwidth. Optical signals are relatively easy to focus, for example using commercial camera optics, because of the small wavelength. The negligible time of flight means that sampling rates can be tens of MHz (although in practice will be limited by processing and the sensitivity of the photodetector); compare this with sonar where typically a single reading takes tens of milliseconds because of the slow speed of sound. Although the electronics and optics is more complex, various low cost sensors have been reported which exploit the advances in laser diode and optical detector technology. In this paper we describe sensors which use modulation to overcome background interference.

The commonest range sensors use triangulation to image reflections from an active source onto a CCD detector. Typical low cost CCD technology acquires images at frame rates of 25 or 50Hz and does not have high enough bandwidth to detect modulated signals. Bandwidth is a problem in all segemented detectors as a whole row of pixels must be read to determine the range of a single point (reducing pixel density improves bandwidth but at the expense of resolution). Equation 1 and 2 show that only one to two measurements are required to determine range in a single angular direction in the modulated sensors.

We have examined the performance of sensors using the two main techniques which will handle modulated signals: one based on phase detection which uses a simple photodiode detector (commonly called an AMCW sensor) and one on triangulation which uses a lateral effect photodiode (which we call the LEP sensor). Although the geometries are different, the sensors share common features in terms of uncertainty mechanisms such as noise statistics because of the similarity in detection devices.

2 Sensor Configurations

To measure over several metres, the AMCW sensor uses a light emitting diode as a source (lasers of sufficient power would be Class IIIB at least). The receiver uses an automatic gain control circuit followed by homodyne detection and phase comparison to determine the phase difference, ϕ, between the transmitted and received signals. The range, R, is related to ϕ through the wavelength λ by the relationship:

$$R = \lambda \frac{\phi}{4\pi} \qquad (1)$$

The maximum range is limited to $\lambda/4$ to avoid ambiguity, or to lower distances by poor signal to noise ratio. Using a 40mW diode modulated at 5MHz, ranges of up to 15m (on the limit of ambiguity) have been achieved [1]. The sensor described in this paper had a 2mW

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source.

The LEP sensor uses a 1mW Class 2 visible laser source. The triangulation geometry converts range to detector offset, p. The offset p is related to the currents at the two detector terminals, I_1, I_2, according to the equation:

$$p = \frac{I_1 - I_2}{I_1 + I_2} \tag{2}$$

The receiver uses coherent detection to demodulate the laser signal. Coherent detection picks out the desired signal from all background intereference. Coherent detection corresponds to a matched filter, optimising signal to noise ratio [2]. Our sensor will operate down to about 3dB above the calculated noise threshold whch takes into account electronic noise sources (thermal and shot noise) [3].

The LEP sensor is modulated at 10kHz. Using a high modulation frequency for the AMCW sensor increases the sensitivity, since the phase shift is greater for a given range; the limit on the modulation frequency is determined by the maximum range to be measured. The phase difference may be measured at lower frequencies through mixing with a local oscillator, since phase is preserved in this operation. In the LEP sensor, the modulation is simply to distinguish the signal from background light sources and a lower frequency is used for convenience. It is best to use the lowest frequency compatible with the required sampling rate so the noise bandwidth can be kept low.

3 Feature Extraction

To make the best use of information, the *quality* of each range reading as well as the estimated value is required. Variance is a common measure of quality. Most work on optimising information simply predicts variance from measurements, treating the sensor as a black box. This is a poorly founded technique especially as systematic errors may not be detected; it also places no bounds on the results in terms of factors such as signal to noise ratio and signal current. We have *analysed* the sources of noise to develop fundamental limitations on accuracy and performance for both sensors. Both sensors have been designed so that thermal noise dominates over most of the range. This is very convenient as it is then easily shown that in the LEP sensor the amplitude of the signal received acts as a measure of variance [3]. In the AMCW sensor, the causes of uncertainty are more complicated, but at moderate signals the same dependence holds [4].

For obstacle avoidance, algorithms used typically are for feature detection and tracking. The Kalman filter is especially popular, and is often described as optimal. However it is optimal only under certain conditions, which include a Gaussian noise distribution and the correct estimation of the variances in measurements and model. Our work has improved the convergence and accuracy of signal processing algorithms since we can *measure* the variance of each reading through recording the amplitude of the signal and has placed bounds on assumptions on probability distribution.

4 Assessment

Hebert and Krotkov [5] suggest that AMCW methods offer the most accurate method of high bandwidth sensing. Our work suggests that that this is true only at longer ranges. Results on AMCW sensors in the literature [6] suggest that the LEP technology give greater accuracy up to about 75cm (normalising the reported results to eliminate variable factors such as aperture size, bandwidth, source power etc). As the triangulation gain adds an extra attenuation dependent on range, at longer ranges phase detection *is* the more accurate method, at the cost of more complex circuit design.

In the LEP sensor we achieved resolution (defined in terms of the standard deviation of a histogram of 1000 measurements) of better than 0.1% at distances up to 0.75m (see Table 1). Our results show that the technology has applications in inspection as well as robot guidance even with eye safe sources.

Table 1. **Ranging accuracy**

range(m)	SD (cm)	% accuracy
0.75	0.05	0.067
1.0	0.148	0.148
1.25	0.463	0.37
1.5	0.798	0.532
1.75	1.568	1.1
2.0	2.547	1.27
2.25	3.713	1.65
2.5	7.662	3.06

A major limitation on accuracy in AMCW sensors is achieving phase stability in the demodulation stage. Although the sensitivity of phase detection can be improved by choosing a higher modulation frequency (which causes a larger phase shift for the same range), achieving phase stability is harder as the frequency increases. Phase stability in the receiver is less critical in the LEP sensor; it affects signal to noise ratio but not the range measurement itself.

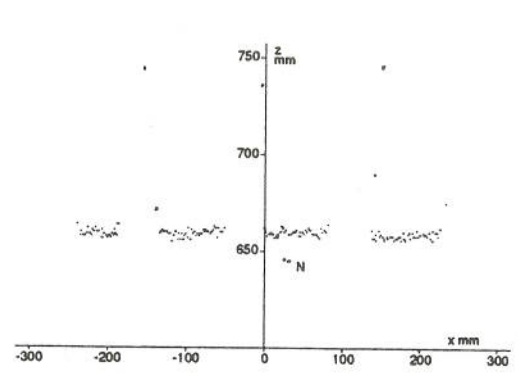

Figure 1: Application of the LEP rangefinder in pallet inspection. The point N marks a nail protruding a few mm from a wooden pallet. Scales in mm. No data processing except calibration.

Further errors occur through a number of failure modes. In the LEP sensor, which uses a low power laser diode as the active source, the main difficulties are those usually associated with triangulation sensors - occlusion and internal reflections from inside corners. We have developed simple rule based techniques so that such features are detected and removed in image interpretation. In sensors which use a light emitting diode as source, a particular problem is caused by returns from more than one surface. We have shown that such points, which are commonly called mixed pixel points, can be distinguished from 'real' range points in the AMCW sensor through analysing the interference pattern and, in particular, the amplitude profile across split features [4]. The success of the algorithm is clear from Figure 2.

Results

Finally we show typical scans for the two sensors. The AMCW sensor was developed to locate free space over a 360° scan whereas the LEP sensor probed the local environment to locate features accurately.

For line segmentation in both sensors we used predictive methods, followed by a validation gate. For the AMCW sensor we simply ran a Kalman filter; in the LEP sensor we used a regression technique, weighting the error in each point by its measured variance.

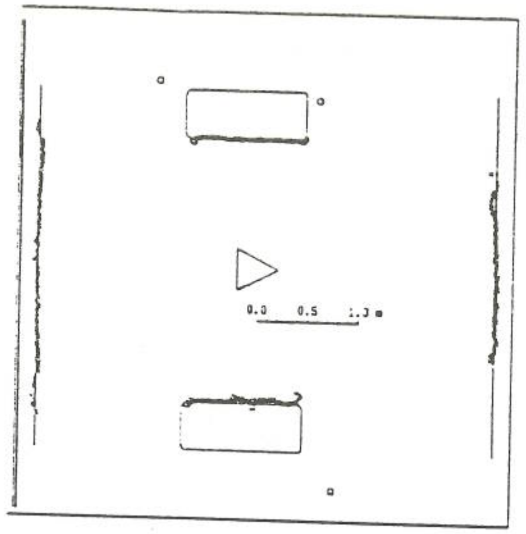

Figure 2: An AMCW range scan in our AGV laboratory. Early processing has been performed: calibration, integration over 10 points, and the removal of low amplitude and mixed pixel range points.

Conclusions

There is very little application of technologies other than CCD cameras in the manufacturing environment. Our work has shown that other technologies may outperform CCDs and offer a low cost alternative, particularly in terms of high bandwidth and tunable insensitivity to background interference. We have demonstrated their applicability in inspection and in mobile robotics.

References

[1] M. Brownlow. Private communication, 1992.

[2] J. Minkoff. *Signals, Noise and Active Sensors.* AT and T, 1992.

[3] N.E.Pears and P.J.Probert. A lateral effect photodiode based scanning sensor for autonomous vehicle obstacle avoidance. In *1st IFAC Intl. Workshop on Intelligent Autonomous Vehicles*, 1992.

[4] M.D. Adams. *Optical Range Data Analysis for stable target pursuit in mobile robotics.* PhD thesis, Oxford University, 1992.

[5] M. Hebert and E.Krotkov. 3-D measurements from imaging laser radars: how good are they? In *RSJ/IEEE International Workshop on Intelligent Robots and Systems*, pages 359–364, 1991.

[6] J. Molnar H.Hofler, G. Schmidkte and L.Unger. 3-*d* measurement techniques for robotics and quality control with structured illumination. In *25th ISATA Proceedings*, pages 81–88, 1992.