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Design and Evaluation of Low Cost Flow Sensor for Irrigation Water Management in Sri Lanka

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EXECUTIVE SUMMARY

A collaborative research project was undertaken with the main objective of Designing and Evaluation of a Low Cost Electronic Flow Sensor for Irrigation Management in Sri Lanka. Other secondary objectives of the project were to establish a collaborative link with Virginia Polytechnic & State University (Blacksburg, Virginia, USA), train an academic staff member at M.S. level during the project duration, procure equipment to strengthen the capabilities of University of Peradeniya in the field of Micro Electronics Applications in Agriculture and publish the research findings in a suitable international forum. This final report covers the project accomplishments over the project duration from the year of commencement (1987) to the end of project termination in December 1990.

The project has achieved its major objective of designing the flow sensor at cost much lower than the projected cost. Of the secondary objectives, establishing a collaborative link with Virginia Polytechnic & State University, training of an academic staff member in the USA at MS level (who actually accomplished the major project objective) and presentation of the research finding at the Annual sessions of the American Society of Agricultural Engineers were achieved as targeted. However, procurement of equipment to strengthen the capabilities of the University of Peradeniya was not possible due to problems which are described in detail in the main body of the final report.

As for the overall impact of the project in the Developing country (Sri Lanka) the trained academic has returned to the country following the completion of his post graduate studies and is currently developing the field of Micro Electronics Applications in Agriculture as a speciality field which was a major achievement of the project. Also the experienced gained during the project implementation had provided valuable insights to further improve and reduce the cost of the flow sensor and work is under way to achieve this end.

TABLE OF CONTENTS

1.0 RESEARCH OBJECTIVES 1

2.0 METHODOLOGY 2

3.0 IMPACT, RELEVANCE AND TECHNOLOGY TRANSFER 3

4.0 PROJECT ACTIVITIES/OUTPUTS 4

5.0 PROJECT PRODUCTIVITY 4

6.0 FUTURE WORK 5

1.0 RESEARCH OBJECTIVES

The Problem:

The economy of Sri Lanka similar to many other developing countries in the region is primarily agriculture based. Irrigation rehabilitation and management for agricultural development is a major policy objective of the government of Sri Lanka. However, management of the scarce water resources, particularly in the dry zone areas of the country which consists of two thirds of the country's land area, has not being satisfactory considering the returns to investments. Efficient irrigation management not only helps to achieve the primary policy objective of the government but also to achieve increased productivity per unit of scarce water resources. Lack of information on irrigation flows is perceived as a major impediment for efficient management of the irrigation systems in the country. Simulation modelling and other sophisticated management which are available cannot be implemented without cost effective instrumentation and has been a major draw back in this context. Thus the major project objective was to solve the problem of cost effective instrumentation which facilitate a wider application thereby assisting better management of water resources.

Research development in the field of electronics in the developed countries has made it possible to design electronic instrumentation at a very much lower cost. This field has not been well developed in Sri Lanka. As such a collaborative link was necessary to obtain the transfer of technology. Virginia Polytechnic & State University in Blacksburg Virginia (VPI&SU) was selected as the collaborating institution for this purpose. Also development of the local capability was considered paramount to the future impact of the project. As such a training component at graduate level at VPI&SU was built into the project to train an academic staff member from the Department of Agricultural Engineering, Faculty of Agriculture University of Peradeniya. The other project objectives were to procure equipment to strengthen the capabilities of University of Peradeniya in the field of Micro

Electronics Applications in Agriculture and publish the research findings in a suitable international forum.

2.0 METHODOLOGY

Methodology adopted contained several phases. The first phase of the project was to send the selected academic staff member from University of Peradeniya to VPI&SU to commence the research work at MS level project. A thorough literature survey to determine available methods of flow sensing instrumentation and their cost effectiveness was a part of the phase I.

The second phase consisted of selecting a suitable design to improve upon with micro electronics to reduce the cost of instrumentation and laboratory test the designed flow sensor. The flow sensor consisted of two components.

1. A water level sensor
2. A data logger (data acquisition system)

The projected cost estimate to design these components was about US$ 500.00.

The third phase consisted of actual field testing of the sensor and the data acquisition system in Sri Lanka to evaluate its performance to overcome possible problems. Scientists from VPI&SU were expected participate in the process of field experimentation together with the trainee and the local counterpart.

The attached M.S. thesis of Mr. P.M.K. Alahakoon (academic staff member) provides the detailed methodological procedure, laboratory tests and statistical analysis of the results. These results are not presented in the report for the purpose of brevity in presentation.

The major findings of the project are summarized in this section to present the achievement of major goal of the project.

a) The flow sensor designed uses the principle of capacitance to sense changes in water levels which can be then reduced to actual volumes of flow. The accuracy of the sensor was ± 1.7 cm after correcting for temperature. The cost of the sensor is about US$ 25.00

b) The data retrieval system was designed at a cost of US$ 220.00

The achievements of the project in terms of cost reduction is highly significant which permits wider practical application of the devices to monitor irrigation flows.

3.0 IMPACT, RELEVANCE AND TECHNOLOGY TRANSFER

Suitable commercialization can make a significant impact on irrigation management if the devices can be mass produced to further reduce the cost. Also economics of the device compared to its commercial counterparts makes it possible for wider application of the technology to solve irrigation management problems.

The project also has shown that simple technology can be transferred to developing countries through collaborative projects. Not only technology can be transferred but also to develop technical skills of individuals in the developing countries to be of service to their motherland. Return of Mr. Alahakoon following his training in the US through the project has opened up a new field in electronics applications in Agriculture in the Department of Agricultural Engineering. Also his training had a significant impact on communication by developing an E-mail network with the other Universities in the country and rest of the world.

Results of the project has opened the minds of the scientists to possible improvements and simpler technology for flow monitoring and work is already under way in collaboration with the International Irrigation Management Institute in Sri Lanka to apply the technology in simulation modelling in irrigation management.

Procurement of equipment for the University of Peradeniya and exchange visits of scientists from VPI&SU were some of the envisaged project objectives. The former was not possible due to communication problems with AID Washington and VPI&SU. The latter was not possible due to the civil unrest that prevailed in Sri Lanka during the project period.

4.0 PROJECT ACTIVITIES/OUTPUTS

1. Design of the Flow sensor and data logger
2. M.S. Level training of Mr. P.M.K. Alahakoon (Lecturer). Subsequently he completed his Ph.D. in the field of Agricultural Engineering and returned to Sri Lanka.
3. M.S. Thesis (unpublished) on "Low cost Electronic Water Level Sensor for Irrigation Water Management", VPI&SU, Blacksburg, Virginia.
4. Three papers were presented at the annual sessions of the American Society of Agricultural Engineering.
5. Procurement of some equipment for the VPI&SU.
6. A visit by Dr. John Daly from the Office of Science Advisor, AID/Washington to Sri Lanka to review project progress
7. A visit by Mr. Griffith Shay from the Office of the Science Advisor, AID/Washington to Sri Lanka to review project progress.
8. A visit by the Sri Lanka principal investigator to VPI&SU to review project progress and preparation of a revised proposal for project extension.
9. A collaborative project with the International Irrigation Management Institute on further improvements to water level sensor.

5.0 PROJECT PRODUCTIVITY

In terms of productivity, the project has achieved its major goals. However, exchange visits that were envisaged by the project were not possible due to the civil disturbances that prevailed in Sri Lanka during the entire project period from 1987 to 1990. It was unfortunate that safety and security of the visiting scientists could not be guaranteed under the circumstances that prevailed. Had this occurred as envisaged in the original project proposal it would have lead to a much better understanding amongst the scientists of the two countries in solving problems in a developing country like Sri Lanka.

Also the purchasing of equipment envisaged through the project for University of Peradeniya did not materialize due to problems of communication between USAID/Washington, USAID/Sri Lanka and University of Peradeniya. These problems were discussed with the visitors from AID/Washington. Unfortunately however, no effective solution emerged to solve the problem. As a result a large proportion of the money allocated in the project for this purpose remained unspent. Had this been possible it would have strengthen the contribution of Dr. Alahakoon upon his return to Sri Lanka to further activities in his field of speciality.

6.0 FUTURE WORK

The activities of the project has given new directions to improve the water level sensor and the data logger. A collaborative project is under way with the International Irrigation Management Institute in Sri Lanka to further improve the water level sensor for the purposes of simulation modelling of irrigation flows.

Low Cost Electronic Water Level Sensor for Irrigation Water Management

by

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Virginia Polytechnic Institute and State University
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Master of Science
in
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Table of Contents

List of Illustrations

List of Tables

Introduction

The art of irrigation extends back to the ancient history of mankind showing a close relationship to the perpetuity of civilization. The rise and fall of civilizations seemed to be dependant mostly on intelligent practice of irrigation techniques which ensured permanently profitable agricultural systems.

In China more than 4000 years ago the success of kings was measured by their wisdom and progress in water control activities (Hansen, Israelsen, and Stringham 1980). Egypt added the world's oldest dam to historical records showing proof of a well-developed irrigation system (Hansen, Israelsen, and Stringham 1980). The following inscription on the tomb of an ancient Assyrian Queen shows the interest taken by them on developing a successful irrigation system (Hansen, Israelsen, and Stringham 1980).

'I constrained the mighty water to flow according to my will and led its waters to fertilize lands that had before been barren and without inhabitants.'

Man-made reservoirs and irrigation canals were in abundance in ancient Sri Lanka, making it possible for farmers to cultivate twice in a year (Goonasekere 1985). There is similar evidence of irrigated agricultural systems which are thousands of years old, in Syria, Persia, Java, India, and Italy.

These highlight the importance of irrigation technology and shows how it has been utilized by man from ancient times (Hansen, Israelsen, and Stringham 1980).

Leonardo Da Vinci, (1452 - 1519) who proved himself to be a genius in every field, expressed his thoughts on irrigation principles and related topics (MacCurdy 1938):

'By the making of the Martesana canal the amount of water in the Adda is lessened owing to it being distributed over many districts in order to supply the meadows. A remedy for this would be to make many small channels because the water which has been drunk up by the earth does no service to anyone, nor any injury because it has been taken from no one; and by the construction of such channels the water which before was lost returns again and is once more of service and use to mankind. And unless such channels have first been constructed it is not possible to make these runlets in the lower-lying country. We should say therefore that if such channels are made in the Martesana, the same water, drunk in by the soil of the meadows, will be sent back upon the other meadows by means of runlets, this being water which had previously disappeared; and if there were a scarcity of water at Ghiara d'Adda and in the Mucca and the inhabitants were able to make these channels it would be seen that the same water drunk in by the meadows serves several times for this purpose'.

This gives a very clear indication of the knowledge and understanding of ancient man on irrigation and its uses. The following sentence found in Da Vinci's note books shows his knowledge on water management and flood control (MacCurdy 1938).

'The canals ought always be provided with sluices, so that excessive floods may not damage or destroy the bank and the water may always maintain itself in the same volume'.

And so, man continued his effort in studying and controlling nature for his own benefit.

A major portion of agricultural lands requires irrigation for optimal production and irrigation is not confined to land which undergoes severe droughts. In order to have profitable and diversified cultivation, closely monitored and systematic water application is a necessity. Therefore, it should be emphasized that only a proper practice of the art of irrigation would give rise to profitable and stable agricultural systems. For this reason man has been encouraged to develop theories and techniques to achieve intelligent control of irrigation systems, which paved the way to the modern subject called Irrigation Water Management.

Irrigation can be defined briefly as the application of water to soil in order to provide necessary moisture for plant growth. More explicitly, it is the application of water to soil for any of the following purposes:

1. to add water to soil to supply the moisture essential for plant growth;
2. to provide crop insurance against short duration droughts;
3. to cool the soil and surrounding atmosphere, making it a more favorable environment for plant growth;
4. to reduce the hazard of frost;
5. to wash out or dilute salts in soil;
6. to reduce the hazard of soil piping;
7. to soften tillage pan and clods;
8. to delay bud formation by evaporative cooling;
9. to facilitate application of necessary chemicals with water.

Several methods of irrigation are in present day use. The most appropriate technique is chosen by taking into account several factors such as water requirement, soil type, plant characteristics, location and topology, availability of water, required power supplies if any, and profit- expenditure trade-off. Methods of irrigation in common practice are:

1. sprinkler irrigation,
2. trickle irrigation,
3. flooding (surface irrigation), and
4. sub-surface irrigation.

All irrigation managers face the general problem of deciding when to irrigate and how much water should be applied each time. An immense amount of research and many experiments have been done on this subject since ancient times. The factors influencing the time of irrigation and the water requirement can be classified into three groups as follows:

1. water needs of the crop,
2. availability of water for irrigation, and
3. capacity of soil to store water once it is applied.

Growing plants use water continuously for biological reactions, but the rate of consumption of water varies with factors such as the type of crop, degree of maturity, and atmospheric conditions including humidity, wind, and temperature. Most of the crops cultivated under irrigation need moderate amount of soil moisture. Growth is significantly retarded by either excessive or deficient amounts of water in the root zone. If the irrigation water supplied causes flooding, it removes entrapped air in soil which is also essential for healthy growth of plants. On the other hand, low soil moisture caused by lack of irrigation drastically reduces the water availability to plants because most of the water molecules in the soil are tightly bonded with soil particles. Prolonged deficiency of available soil moisture causes permanent wilting of plants and therefore needs to be prevented by precise timing of irrigation.

Another important factor which affects the time and amount of irrigation is the pattern of water removal by plant roots. Hansen, Israelsen and Stringham (1980) found that crops with shallow roots require more frequent irrigation than deep rooted crops because those absorb most of their water from the topmost layers of soil. In order to keep the top layers of soil sufficiently moist, frequent irrigation is required when no rainfall occurs. Since shallow rooted plants are unable to extract moisture from deeper layers of soil, irregular or insufficient irrigation would cause permanent damage or retardation of growth.

As mentioned above, the consumptive use of water by crops also varies with their stage of growth. The growth of a plant could be divided into three stages when considering irrigation practices: vegetative, flowering, and fruiting. Consumptive use of water increases as a plant grows and reaches its peak at the beginning of the flowering stage. Plants tend to decrease their water consumption and ceases to absorb water when the final dormant stage is reached. During the vegetative period, a good moisture supply should be maintained by frequent irrigation. As the plant grows, its roots tend to penetrate deeper and absorb water from deep soil layers. Water consumption then decreases with the completion of fruit growth and stops when the plant reaches its dormant stage following the dry fruit period. The amount of water applied and frequency of irrigation should be carefully planned to meet the water requirements of the crop which varies as it grows through different stages as described above.

The factors discussed above indicate the importance of maintaining soil moisture during different periods of plant growth and emphasize the necessity for intelligent irrigation water management. Therefore, different techniques and methods have been developed in every part of the world for the purpose of improving irrigation management. Good management of irrigation water requires that both the time of application and amount of water applied be precisely planned. Therefore, techniques of measuring irrigated water play an important role in the development of agriculture. Each of the irrigation methods mentioned above is accompanied with different ways of estimating the amount of water supplied.

The most common method of irrigation practiced in developing countries is flooding. It is done by applying water to the field through a network of open ditches. In order to achieve maximum benefits from the limited sources of irrigation water, it is necessary to control the amount of water applied (Schwab et al. 1981). The importance of controlled irrigation has previously been discussed from the standpoint of water requirements of plants.

Research studies have shown that the worldwide total of irrigated land in the mid 1980's was about 560 million acres. The most important fact is that the acreage possessed by developed countries is only 78 million acres (Skeller 1986). Therefore, developing countries contain about 86% of irrigated agricultural land.

Fairchild and Nobe (1986) state that during the 10 year period from 1976 to 1986, approximately 40% of all increases in food production in developing countries have come from expanded irrigation. They further make the following statements about irrigation in less developed countries. Water has been treated as a freely available item even though operation and management costs including water charges lies above the average agricultural income. This situation results in wastage of water and a loss of food production potential, which is directly translated to a drain on financial resources of these countries. Current studies (Fairchild and Nobe 1986) indicate that water for irrigation rather than the land area available for cultivation will become the limiting natural resource in agricultural development in the future.

Therefore, irrigated agricultural systems, being one of the most important factors to the economic development of the large number of less developed countries, needs greater attention towards establishing proper management structures.

Major investments have been made by many governments in irrigation system development as the primary step to increase the agricultural productivity. But, frequently such irrigation development works have failed to produce the intended improvements in agricultural productivity due to poor management of irrigation water. Wicham and Valera (1978) mention that: 'While it is generally agreed that better water management is needed, it is not clear what is required to achieve it. What do we really mean by improved water management, how it can be attained?'

It is important to be able to control the amount and rate of application of water in order to achieve optimum results from irrigation. One of the most difficult systems to monitor effectively is canal type irrigation systems, which also are the most commonly used systems in less developed countries due to the fact that it is the least expensive to build. The difficulty faced by the system manager is the lack of information on the fluctuation of the water levels which affect the discharges throughout the irrigation system. These water level fluctuations are mainly due to overuse at upstream locations, illicit water tapping, and losses through improper gate settings. It is known that if the system manager is provided with information on these water level fluctuations, he will then be in a better position to estimate discharges within the channel system. The availability of a water level sensing and recording system which can be widely used in such irrigation systems would improve water management and hence provide substantial benefits for overall development of agriculture.

There are some manual devices for measuring and regulating water flow through canals such as weirs, flumes, and division boxes which are presently in use. There are two means by which the discharge into any distributory offtake can be controlled. The first is the regulation of the water elevation at the distributory canal. The second is the control of gate settings at the outlet openings. But in the absence of the former, which requires proper measurement of water level, the latter becomes totally ineffective. Even though very sophisticated devices have been built for the purpose of sensing and recording water level in such systems, the high expense of these devices keep them from being widely used.

Sri Lanka has been proposed as the sensor test site in this study. In ancient Sri Lanka, the initial phase of irrigation began with the construction of temporary weirs and anicuts across perennial streams that diverted water into a system of contour canals. This setup was further developed and expanded with the construction of reservoirs (tanks), sluice gates, and access towers for the controlled release of water for irrigation (Goonasekere 1985).

Goonasekere (1985) also writes that the Mahaveli diversion scheme, which had its inscription in the mid-1960's was expected to be the major source of irrigation water for the dry zone of Sri Lanka. The diverted water was supplied to farmers through a system of reservoirs and canals.

Even though this scheme improved the water availability throughout the year, the attention paid to the management or the actual end use of water by farmers was insufficient (Goonasekere 1985). He further clarifies the general nature of the existing water management problem in Sri Lanka as follows: 'The irrigation system managers emphasize that most of the problems are at the farm level and are caused by farmers. The other school of thought is that the system causes most of the farm-level problems. The argument they present is that, when the water supply becomes unreliable due to defects in the technical system, its management, and operation, the farmers react to the situation by using as much water as possible when it is available. Therefore, the implication is that water supply should be first made reliable by removing the management and system defects in order to solve the problem at the farm-level.'

This approach calls for better techniques for irrigation water management. If the system manager could be supplied with more reliable data on water levels in irrigation canals, he will then be in a better position to estimate the water flow through the system by incorporating several other parameters such as channel dimensions and flow rates. Therefore, he would be able to make a better decision in the process of water regulation and control by comparing the water needs of the crop and water supplied to the field.

Because all widespread irrigation systems in Sri Lanka are owned and maintained by government organizations (Goonasekere 1985), and provided as a service to the farmer, it has been difficult to equip them with expensive measurement and control devices available in the current market. The approach in this study is to design and build a Sensor - Data Logger unit for the improvement of water management facilities. In particular, the problem of sensing the water level in canal type irrigation systems and recording of digital data for the purpose of continuous monitoring will be dealt with in this study.

Objectives

The principal goal of this investigation was to develop a low cost water level sensing device and evaluate its performance and applications in improving irrigation water management. The emphasis was on electronic level transducers and digital data output, which enable the system to be used as an automated data acquisition system.

The following steps were taken to achieve this goal:

1. study the operation of available water level sensing devices and their cost-performance trade-off;

2. select three different systems for preliminary studies;

3. analyze the systems, study the design requirements and construction constraints;

4. design and build the two most feasible devices, test in a laboratory environment, examine the performance and make necessary improvements;

5. develop an automatic data logging system incorporating these sensors; and

6. analyze the expenses in comparison with other available systems.

Review of Literature

Introduction

There are numerous methods of irrigation in present day use. As it was essential to estimate the amount of water in each case in order to achieve proper control and benefits, different techniques have been developed for the purpose. The most common practice of irrigation in developing countries has been surface irrigation through canals and ditches because it was generally considered as the easiest and cheapest system to build. In most situations, gravity flow was used with control structures to guide water as required. In response to the demand for higher production, it was necessary to improve measurement and control of irrigation water to improve yield. Even though several mechanisms have been developed for controlling water flow through pipes and pumps, efficient regulation of open channel flow needed further attention. Even though several devices for measuring stage have been developed, their high price prevent them from being widely used in less developed countries, where it is needed the most.

The earliest type of level measurement can be classified as using point contact devices. In its most primitive form, a notched stick was used which provided a rough measurement of height of water above an arbitrary reference point. Man's perpetual effort to make his activities more refined and accurate, led to the design of the hook gage, point gage, and steel tape and plumb-bob gage, which make use of the same principle of measuring the distance to the top surface of reservoir from a fixed datum line (Considine 1957).

Another accurate and fairly versatile manual device of measuring water level was the development of the Gage glass. This consisted of separate graduated vertical glass tube attached to a tank. Liquid level change in the glass tube was the same as that inside the tank and a direct measurement of level could be taken once a datum was fixed. These devices still remain popular in applications where direct reading of level and accuracy involved are satisfactory.

Types of Level Sensors

A large amount of research has given rise to numerous ways of sensing liquid level with various degrees of complexity, in cases where continuous or discrete measurement is required. Norton (1969) lists some of the basic properties used for level sensing:

1. buoyancy,
2. cavity-resonance,
3. electrical conductivity,
4. dielectric properties,
5. heat transfer characteristics,

6. response to nuclear radiation,

7. optical properties,

8. pressure,

9. response to sound waves,

10. viscous damping effects, and

11. weight.

Buoyancy Sensors

Buoyancy sensing utilizes the Archemedes' principle - a body submerged wholly or partially in a liquid is buoyed up by a force equal to the weight of the fluid displaced. Various types of transducers have been built using this principle for both discrete and continuous measurements and control. Hamm (1952) briefly describes some of the float actuated techniques as:

1. float-switch type controller,

2. automatic type liquid level indicator,

3. float type chart recorder,

4. magnetic liquid level controller, and

5. direct reading float type gage.

Some of these transducers are of discrete type and others are especially made for the cases where continuous observation is required.

Cavity Resonance Sensing

Norton (1969) mentions cavity resonance sensing as a technique used to measure the amount of liquid inside a closed tank. The technique utilizes the resonance characteristics of a closed cavity which changes with liquid level. High frequency electromagnetic oscillations are emitted into the tank and the resonance frequency is sensed. As the liquid level changes so does the resonance cavity size above the liquid and corresponding resonance frequency, making it possible to estimate the liquid level inside, provided that geometry of the tank is known. The most common application of this technique is to sense the upper limit of filling a tank by using the resonant cavity as a discrete level transducer, even though it could be used as a continuous level transducer with additional manual controls.

Conductivity Sensing

The level of electrically conductive liquids could be sensed by immersing two electrodes into the liquid and monitoring the change in resistance between them (Norton 1969). Depending on the type of liquid and application concerned, this technique could be used as a discrete as well as continuous type level transducer.

Dielectric Sensing

The dielectric properties of liquids have been utilized in the development of liquid level sensors. The dielectric constant of any substance indicates its ability to act as the dielectric medium inside a capacitor. If the dielectric constant of a liquid is different from that of another fluid with which it is in contact, a composite capacitor which has both liquids as its dielectric media can be used to sense the variation in liquid level. Two or more electrodes have been used where the capacitance varies according to changes in liquid level. The sensing structure is setup so that the liquid rises and falls in the space between electrodes which constitute an electrical capacitor. Due to the fact that one liquid has a higher dielectric constant than the other, the capacitance varies with the amount of liquid entering or leaving the intermediate space of the electrodes and hence with the liquid level concerned.

This type of transducer has been used in various applications where continuous monitoring of liquid is required. Norton (1969) further describes the method employed in sensing the capacitance as a four arm a.c. bridge network which converts the capacitance change to a change in a.c. voltage which could then be used to cause a deflection corresponding to the capacitance change.

Heat Transfer Sensing

The rate of heat transfer from a heated body is higher in a liquid than in air. Resistive heaters and thermoelectric sensors are combined to work using the above phenomena in this type of transducer. The sudden cooling of a heater when touched by a rising liquid is sensed by thermoelectric sensors (Norton 1969).

Nuclear-radiation Sensing

Radiation emitted by a source on one side of a tank is received by a sensor on the other side. Gamma radiation is most commonly used in this type of applications. When the water level has risen sufficiently to interfere with the radiation path the intensity of the received signal is drastically attenuated due to increased absorption by liquid medium. This explains the basic principle behind radiation sensing which is most commonly seen as a discrete type measuring technique.

Optical Sensing

Operation of the optical type sensor is very similar to that of nuclear radiation sensors. A light beam is used to sense the presence or absence of liquid at a pre-determined height. A glass prism is used to divert a light beam away from a sensor with the use of total internal reflection at the glass-air interface. When the medium changes to liquid, the corresponding change in the refractive index drastically reduces the reflected portion of the beam, triggering the sensor. In other cases the reduction of the intensity of light due to liquid is directly sensed (Norton 1969).

Pressure Sensing

The hydrostatic head caused by a liquid in a vessel has been utilized in the development of this type of sensor. Considine (1957) classifies pressure sensing systems as follows:

1. direct connection of hydrostatic head to measuring device,
2. diaphragm-box system,

3. air-trap system,

4. bubbler type or purge system,

5. force-balance system, and

6. opposed-diaphragm types.

With the invention of piezoelectric strain gages, pressure sensing techniques have been remarkably improved and are in common use today.

Sonic Path Sensing

It has been observed that sound waves are reflected by liquid-air interfaces when emitted either from air medium or from liquid medium. Therefore, the time elapsed between emission of a sound pulse and reception of the reflected pulse represents the distance to the liquid-air interface from the sound projector. Sound waves in the ultrasonic range are commonly used. With modern technology very accurate distance measurements are possible by ultrasound (sonar) devices (Norton 1969).

Damped Oscillation Sensing

This type of sensor uses a piezoelectric element which oscillates in a gaseous medium but stops oscillating, due to acoustic damping, in a liquid medium (Norton 1969).

Weight Sensing

Another common technique for estimating liquid level, volume, or mass is to measure the weight of the fluid. If the geometry of the container is known, measurement of weight can be converted to volume or level using the liquid density and dead weight of the tank (Norton 1969). Load cells are used to sense the weight of the tank and liquid contained in it.

Development of Sensors

The float and weight actuated chart recorder could be considered as the most common device used in water level sensing. However, it incorporates several rotating mechanical parts and has inherent errors due to frictional resistance and back-lash. Begeebing (1935) classified the earliest liquid level sensors into two basic groups: float type and pressure type. It could be seen that historically the development of level sensors was most enhanced by the oil industry. A boost in development of the aircraft and shipping industries during World War I and II caused another significant improvement in this type of technology. Pressure vessels were involved in oil refinery work which needed close supervision and control. This gave rise to differential pressure type level controllers (Begeebing 1935).

Casella & Co. (1931) manufactured a mechanical device by which the top level of a liquid tank could be observed and measured with a great accuracy using a vernier scale. Some of the suggested applications were in engine tests, and determination of pan evaporation rates.

Behar (1941) described the operation of a large number of early types of liquid level sensors and controllers in his extensive survey report. Most of the devices he described use pressure as the sensed property as the liquid level changed. The applications were mostly in level control of liquids in closed tanks such as gasoline reservoirs of engines and boiler tanks.

Among pressure sensing type devices, there were anaroid type sensors, diaphragm operated mercury switch type controllers, and air operated controllers. Many devices have also been developed using a float type actuator. Most of the float type devices were used to maintain constant liquid levels in boiler drums by using the float to automatically open and close inlet valves as required. Behar (1941) also reported of manufacturers who supplied electrode type sensors for controlling liquid levels. Most of the devices sensed the change in current due to the conductivity of liquid and used it to operate relays to achieve proper control. One common feature of all these devices was that they incorporated a fairly large number of mechanical parts to link the primary sensing device to other peripherals such as valves, relays, indicators, and recorders.

Cusick and Jones (1945) described a system especially recommended for measuring the level of corrosive liquids, or in measuring the liquid level of a substance containing entrained or suspended solids. This was done by purging the liquid concerned with air, or another inert gas, or water if applicable. The second medium was used to transmit pressure changes due to varying liquid levels to a pressure sensor which in turn would operate valves by mechanical means. They also described systems which use mercury as the pressure transmitting medium.

A sensor which operated on the principle of electrical resistance was introduced by the Product Engineering (1946) magazine. As the liquid made contact with the electrodes it conducted a minute electric current which, after amplification, controlled relays, valves, or pumps. Another modification in this system was the availability of a sensitivity adjustment which made it possible to control chemical concentrations of liquids as well.

Jones (1948) described an automatic controller which maintained a constant level of low boiling point liquids in a container by controlling the entry of fresh liquid from a reservoir. Regulation was performed by a strong valve actuated by a vapor pressure thermometer and elastic bellows. This device had the advantage of having no external connections or relay systems.

An instrument was introduced by Kovacic (1954) which, by using a sensitive spirit level mounted upon a float, indicated level differences or differential air pressures with a very great accuracy. A slight change in liquid level caused a large displacement of an air bubble of the level giving rise to a higher degree of sensitivity.

Williams and Maxwell (1954) designed an instrument, which operated on the capacitance principle, to measure, indicate, record, and control level of liquified gases inside a closed vessel. The sensing element was a cylindrical capacitor, whose capacitance was a function of the height of the liquid column. The measurement of capacitance was done by the electrical bridge method. A four arm a.c. bridge was used for the measurement which drove a chart type recording device. Williams and Maxwell (1954) also state that the chief disadvantage encountered was the need for electronic circuitry of fairly high sensitivity.

The strength of the capacitance method lies in its simplicity and adaptability. Installations have been notably successful even under extremely adverse conditions (Hannula 1957). He also mentioned several potential sources of error in the measurement. If the position of one electrode moves with respect to the other during the process, it causes a change in capacitance because of the change in geometry and makes the result differ from the expected. Proper mounting of probes is suggested as a remedy.

In order to compute the instrument range, the dielectric constant of the liquid must be known, and it must remain sufficiently constant to maintain a capacitance of required stability. Because the dielectric constant varies with the composition of the material, a change in the constituents will produce a change in dielectric constant (Hannula 1957).

The temperature dependance of the dielectric constant must also be considered. Temperature variation could be controlled or observations have to be corrected if the changes are significant. He also recommended using bare metal probes when the liquid is nonconductive and insulated probes in the case of conductive liquids.

Hannula (1957) describes another factor affecting the measurement of conductive liquids as 'hang-up'. It is the effect of a thin film of liquid which sticks to the electrodes when the liquid decreases after its risen to a certain level. According to the techniques developed at that time, the following were some of the questions that had to be answered in connection with 'hang-up'. 'Will the process material adhere to the probe insulation? Are there probe materials to which it won't adhere, or can the insulation be skin coated with another substance to prevent it? If the material adheres, how thick is the film, and will it accumulate with time? What is the resistance of the film? Does it remain wet and conductive or dry out and become nonconductive? If it dries, does it dry fast enough to produce adequate measurement response?'.

Capacitance level measurement requires two operations; first, the transformation of level change into capacitance change; second, the transformation of this capacitance change in to meter indication or control action (Revesz 1958). He describes a capacitance type sensor consisting of a single metal probe at the center of a metal tank containing the liquid of which the level is to be measured. He also suggests that the rod be electrically insulated from the vessel wall due to the disadvantages incorporated with bare probe rods. Revesz (1958) listed two problems with bare probe type capacitive sensors, first, materials with high dielectric constants are difficult to measure, and conductive materials cannot be measured at all. Second, corrosive materials require expensive alloys to be used as rod material, thereby making long probes very costly.

Herbster and Roth (1965) report that the capacitance type probe was selected as a commercial tank gage in a survey due to the following reasons.

- it offered adequate precision (± 0.2% of maximum level)

- in-tank elements had no mechanical movement to decrease reliability and were easily protected from corrosion.

- it provided easy installation with minimum tank modification.

- it provided close-to-minimum equipment and installation costs of all methods investigated, where other techniques were radiation sensing, buoyancy sensing, and weight sensing.

Electronic circuitry in a capacitance level - measuring system varies from one manufacturer to another. Basically capacitance change in the tank unbalances a bridge circuit. The unbalance is indicated on a meter, or the bridge is rebalanced electronically and the rebalancing signal is used for indication (Herbster and Roth 1965).

Theoretical Background

The research plan required the development of two prototype sensors for experimental purposes. As mentioned earlier, prime consideration was given to low cost and compatibility with data logging equipment. It could be seen that a major problem encountered in the past with this category of sensors is the difficulty in automated data collection in digital form. Apart from that, the two methods, capacitance type level sensor and float and weight device, proved to be ideal for the intended application. Therefore, those two devices were selected for development. It was necessary to introduce a technique of converting the sensor output to digital format, which facilitates automated data logging.

Capacitive type Sensor

The basic property utilized in the development of this device is the higher value of dielectric constant of water than that of air ($\varepsilon_{water} = 6.79x10^{-10} Fm^{-1}$ and $\varepsilon_{air} = 8.85x10^{-12} Fm^{-1}$) (Giacoletto 1977, ch.2). To develop a theoretical relationship between the water level and capacitance, a simple system consisting of two parallel plate conductors was considered.

The electrical capacitance between two parallel conducting plates has been found to be dependent on the area, distance between the plates, and dielectric constant of the medium between the plates (Fig. 1). Using basic theorems of electricity (Solymar 1984, ch.2) it can be proved that the capacitance of such an arrangement is given by:

$$C = \frac{\varepsilon A}{d} \qquad [1]$$

where:

C = capacitance,
ε = dielectric constant of the medium,
A = surface area, and
d = distance between parallel plates.

The expression for electrical capacitance per unit length of two concentric tubes as shown in Fig. 2 can be derived as:

$$C = \frac{2 \pi \varepsilon}{\ln \left[\frac{r_o}{r_i} \right]} \qquad [2]$$

where:

r_o = radius of outer conductor, and
r_i = radius of inner conductor.

If the tubes are partially submerged in one medium which has a different dielectric constant from that of the other, the total overall capacitance is given by the sum of the capacitances formed by the portion of the tubes in each medium. Referring to Fig. 3, the total capacitance can be derived as:

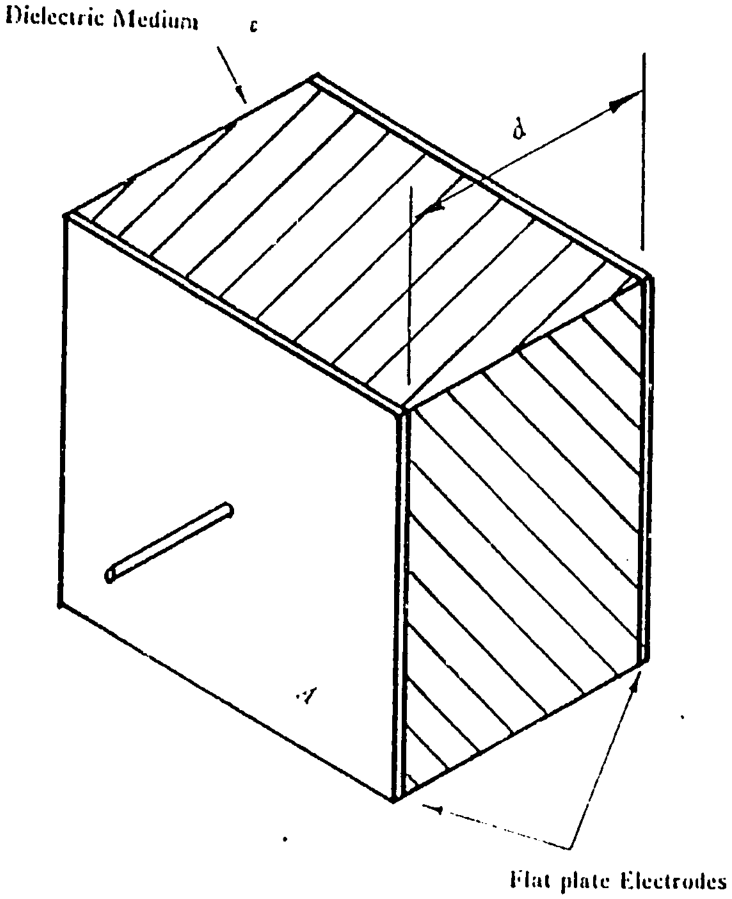

Figure 1. Parallel Plate Capacitor

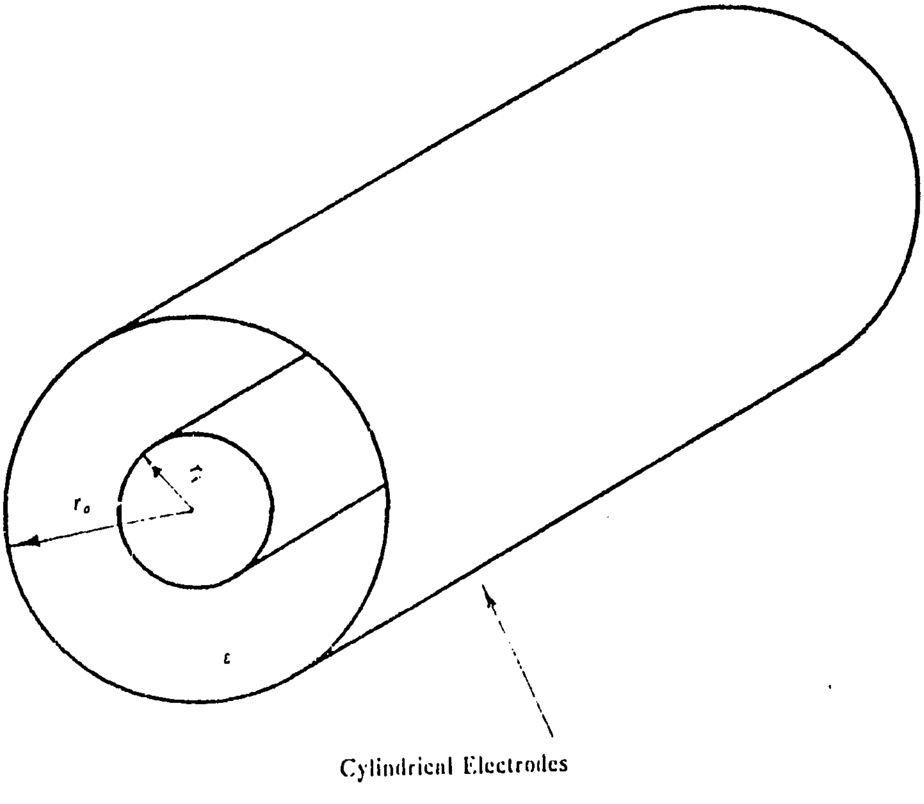

Figure 2. Concentric Cylinder Capacitor

$$C = \frac{2\pi\varepsilon_1 l_1}{\ln\left[\frac{r_o}{r_i}\right]} + \frac{2\pi\varepsilon_2 l_2}{\ln\left[\frac{r_o}{r_i}\right]} \qquad [3]$$

where:

l_1 = submerged length in medium 1,

ε_1 = dielectric constant of medium 1,

l_2 = submerged length in medium 2, and

ε_2 = dielectric constant of medium 2.

Because water has a significantly different dielectric constant than air, a change in the submerged length of the tubes causes an overall change in capacitance of the system. This phenomena has been utilized in the development of this sensor.

Measurement of Capacitance

There are several methods available for measuring capacitances. Whetstone bridge methods and electrical resonance methods have been used for this type of measurement. In this development, resistive charging of the capacitor was employed because it provided a significantly simpler way of converting the capacitance change to digital format than the techniques mentioned above. The time delay of the output to a step change of the input of the resistor - capacitor combination was measured. By assuming the leakage resistance across the capacitor to be very large, the arrangement can be represented by the simplified circuit in Fig. 4. The time variation of output voltage of the sensor V_o in response to a step input of V *volts* can be given as :

$$V_o = V\left[1 - e^{-t/CR}\right]. \qquad [4]$$

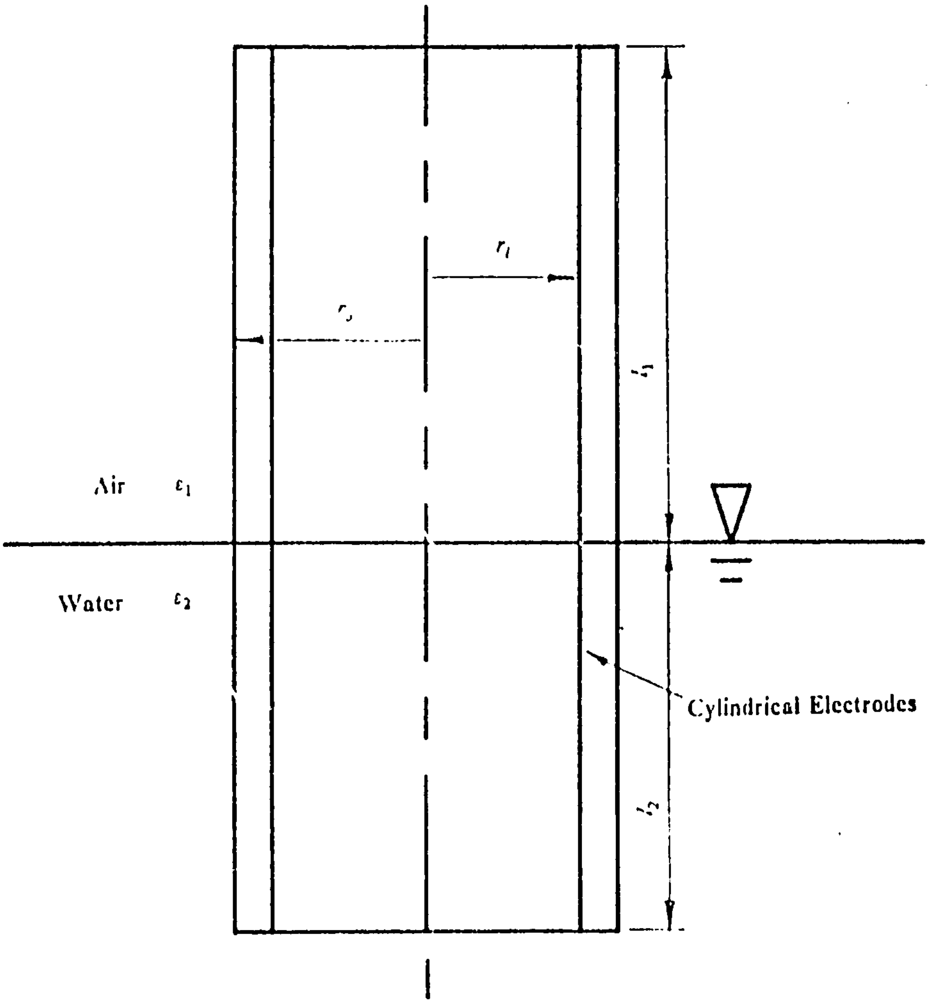

Figure 3. Partially Submerged Composite Capacitor

where:

t = time, and

R = charging resistance.

Time, t, taken to reach a threshold voltage, V_T, is given by :

$$t = -CR \ln\left[1 - \frac{V_T}{V}\right]. \qquad [5]$$

Therefore, the measurement of time directly represents the capacitance if the factors V_T, V, and R are constant. By combining equation [5] and equation [3], it can be shown that the relationship between the delay time, t, and the water level l_2, is linear as shown in equation [6],

$$t = -2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1)\, l_2 - 2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2), \qquad [6]$$

with the only variables being l_2 and t.

Effect of Leakage Resistance

It was assumed in the previous development that the leakage resistance between the electrodes was very large. In practice it may be sufficiently low to cause a considerable change in the output. A simplified equivalent circuit could be derived by replacing the charging resistance R with its Thevenin equivalent (Edminister 1965, ch.11) R_{eq}:

$$R_{eq} = \frac{R R_l}{(R + R_l)} \qquad [7]$$

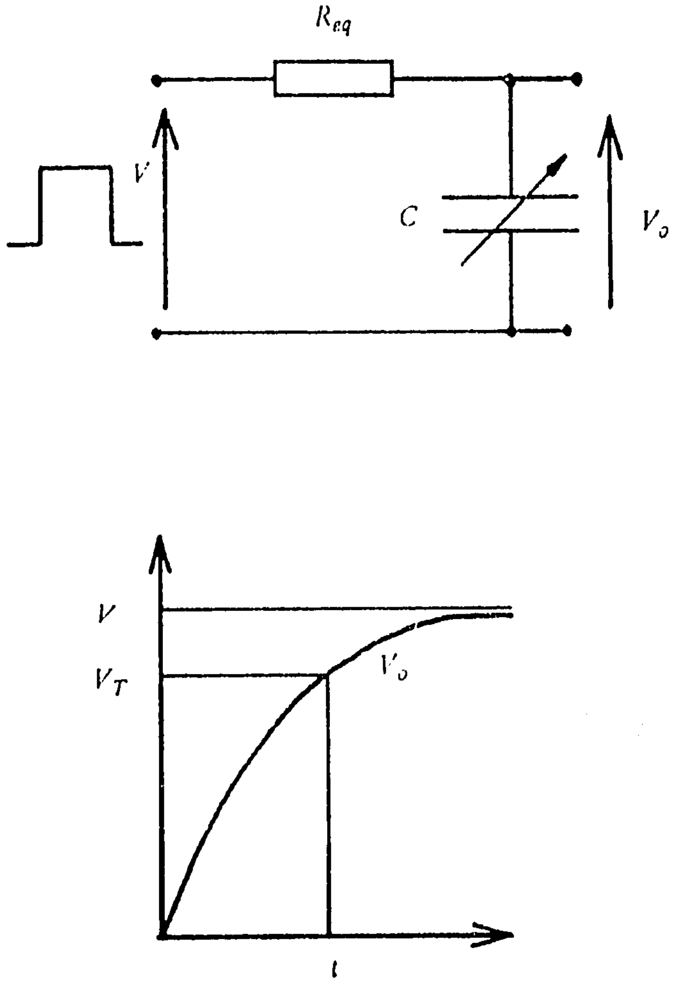

Figure 4. Simplified Excitation Circuit and Output Waveform - Capacitive Sensor

where:

R = charging resistance, and

R_l = leakage resistance of capacitor.

Therefore, the previous expression for delay time t could be easily modified by substituting R_{eq} for R, without changing its linear relationship to water level l_2 (Fig. 4). The modified relationship between the water level and time delay is:

$$t = -2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1) l_2 - 2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2). \quad [8]$$

Potentiometer Sensor

In the search for improved techniques for water level recording systems, it could be seen that the previous idea of resistive charging of a capacitor is applicable to improving the performance of conventional devices such as the float and weight actuated chart recorder. By the use of a potentiometer along with a float and weight type actuator, the resistance R_p is made to vary with water level l as opposed to capacitance C in the previous case (equation [4]). The basic principle of time measurement has been used in the same way as before. Electrical circuit representation of the arrangement is shown in Fig. 5. Using the same principles, as in equation [4], the expression for output voltage could be derived as:

$$V_o = V[1 - e^{-t/CR_p}] \quad [9]$$

where:

V_o = output voltage,

V = input voltage,

C = capacitance, and

R_p = resistance of the potentiometer.

Similarly time, t, taken to reach a threshold voltage, V_T, when activated by a voltage V is:

$$t = -CR_p \ln\left[1 - \frac{V_T}{V}\right]. \qquad [10]$$

A general relationship between the water level l and the potentiometer resistance R_p could be established by considering the mechanical rotation of the pulley and the potentiometer caused by the vertical movement of the float (Fig. 6). A simple analysis on the arrangement provides the relationship in Equation [11]:

$$R_p = \frac{l}{2\pi r_p}\left[\frac{R_{p_{max}} - R_{p_{min}}}{n}\right] + R_i \qquad [11]$$

where:

R_p = resistance of the potentiometer,

l = vertical displacement of float (water level change),

r_p = radius of pulley.

$R_{p_{max}}$ = maximum resistance of the potentiometer,

$R_{p_{min}}$ = minimum resistance of the potentiometer,

n = number of rotations of the potentiometer, and

R_i = initial setting of the potentiometer.

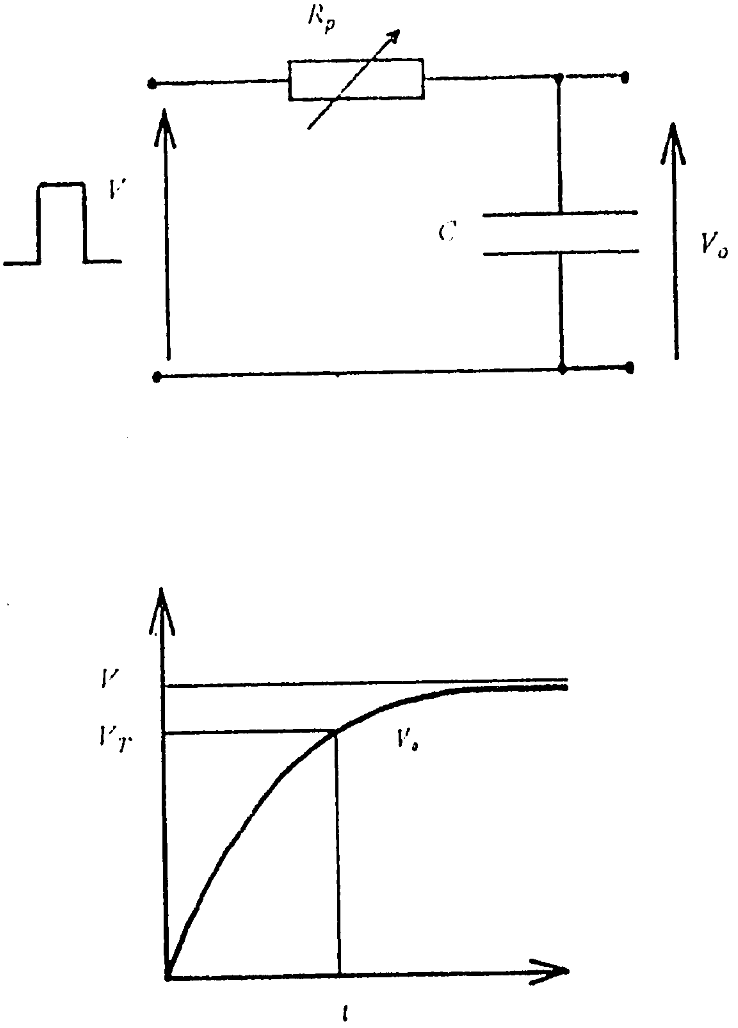

Figure 5. Simplified Excitation Circuit and Output Waveform - Potentiometer

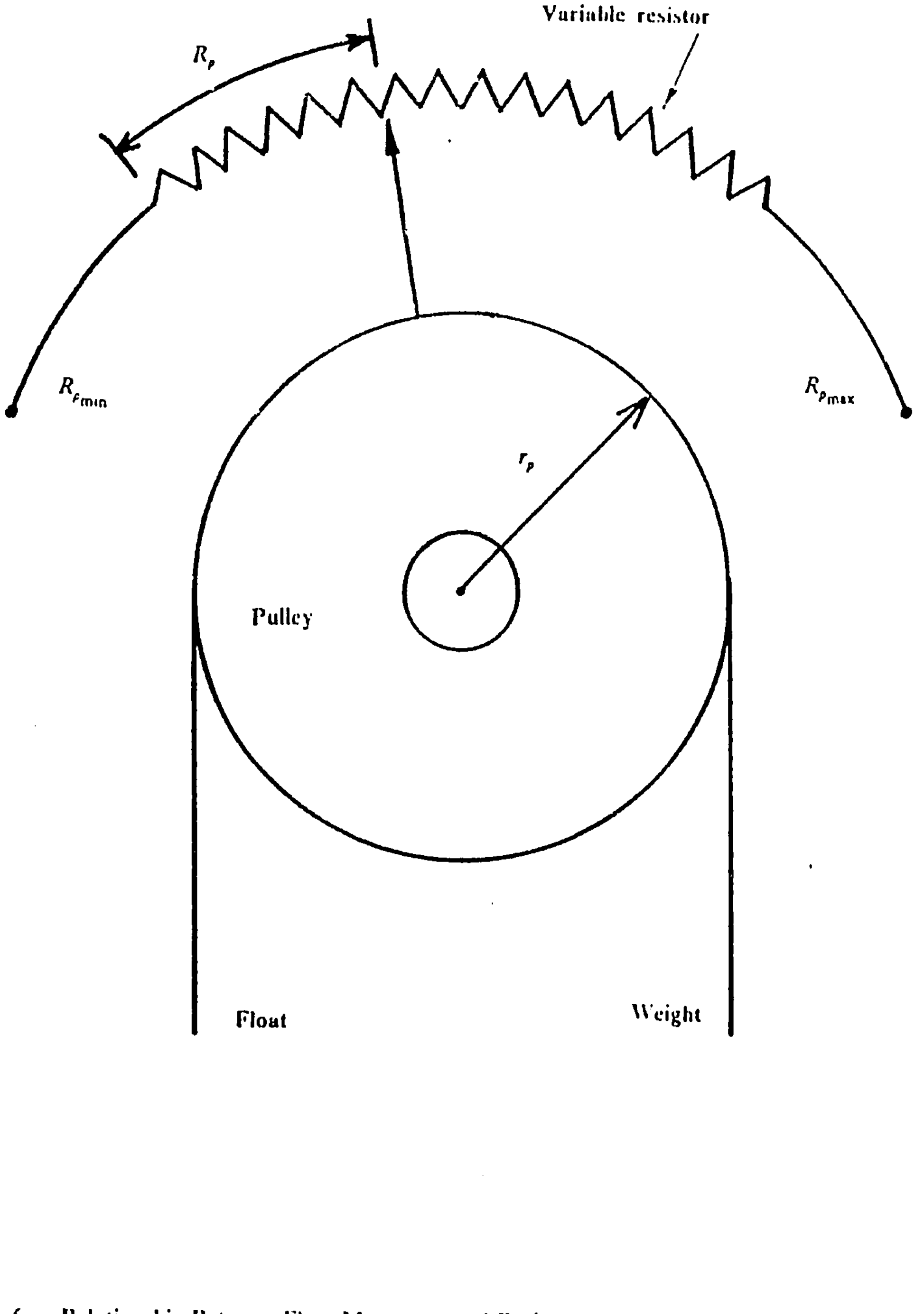

Figure 6. Relationship Between Float Movement and Resistance

This shows that the vertical displacement of float is linearly related to the resistance of the potentiometer at any setting. By measuring the time delay caused by the combination of varying R_p and constant capacitance C, it is possible to estimate the corresponding changes in water level. The complete relationship between water level change, l, and delay time, t, is given below in equation [12], derived by combining equation [10] and equation [11].

$$t = -C\left[\frac{l}{2\pi r_p}\left[\frac{R_{p_{max}} - R_{p_{min}}}{n}\right] + R_l\right] \ln\left[1 - \frac{V_T}{V}\right] \qquad [12]$$

Based on these two theoretical relationships between water level and capacitance (equation [8]) and water level and resistance (equation [12]), the overall behavior of both sensors were expected to be linear.

Ultrasound Device

Ultrasound measurement (Sonar) was considered as another possible method to accomplish the task in this study. But, due to several reasons discussed later, it was decided to proceed experimenting only with capacitive and potentiometer sensors. The theoretical background of an ultrasound distance measurement device is briefly described as follows.

A high frequency sound pulse (e.g. 200 kHz.) is emitted from a transmitter towards the target to which the distance is to be measured. Depending on the physical characteristics of the target object, a portion of the pulse is reflected back and detected by a receiver. The time taken by the sound wave for the complete journey is measured. If the speed of the ultrasound wave through the medium is known, the distance between the transmitter and the object can be precisely calculated.

Another arrangement is to install a receiver at the target plane and measure the time taken by the pulse to reach the target. Sensors have already been developed for water level measurement utilizing both these techniques.

After studying the requirements and characteristics, the following types of sensors were selected for further studies:

1. capacitance probe,

2. potentiometer sensor, and

3. ultrasound device.

Even though ultrasound devices have the capability of measuring distances with a high accuracy, the following characteristics restrained it from being used for this particular application.

1. Power consumption was very high compared to other methods selected. (200 - 600 *mW*) This is not a favorable characteristic for a field instrument which has to be powered by dry battery banks.

2. Voltage requirements were not directly compatible with other BIPOLAR or CMOS devices which usually operate on 5 *V* d.c. Due to this reason, it required the use of additional signal conditioning hardware for the input and output terminals.

Taking these facts into consideration, it was decided to proceed with the other two types by constructing prototypes for preliminary testing.

Design and Development

Capacitive type Sensor

In the design process the first consideration was given to the capacitive type sensor. According to the theoretical analysis, it could be seen that the same technique can be used in various applications where continuous sensing is required. As a first step, factors governing the sensor design were identified for the determination of the other parameters.

Several factors had to be determined before the sensor was constructed.

1. A suitable conducting material for capacitor plates or electrodes had to be identified.

2. A method of insulating the electrodes needed to be found.

3. Height of the sensor - intended range of measurement had to be determined, and

4. Other factors which affect the sensitivity of the capacitive sensor needed to be identified.

Since the main objective in this study is to monitor water levels of irrigation canals, it was suggested that all equipment be installed in stilling wells attached to each irrigation canal. Therefore, it could be assumed that a cylindrical shape would be best suited for this particular application. Considering the wide range of sizes available, and the reasonable cost, it was decided to use Aluminum pipes for the construction of sensors. Selection of cylindrical shape for the sensor capacitor was also justified by the behavior of electric field around concentric cylindrical conductors. This arrangement acts to limit the generated electric field to only the intermediate space between those, when the outside conductor is at ground potential. Cylindrical shape of the tubes also matched the conventional shape of stilling wells and therefore, causes no additional difficulties in installation.

Since the capacitor is to be submerged in water, it was necessary to prevent direct leakage of current between the two electrodes. Chemical corrosion was another problem addressed in the long term use. Therefore, it was decided to insulate the electrodes against current leakages and corrosive chemical reactions.

The conductivity of insulation materials, in this case paints, played an important role in selection process. Several aluminum tubes of length 30 *cm* were painted with four different paints which were commonly available. After the suggested curing time, each of these tubes were submerged in water along with another uninsulated electrode and the resistance between the two were estimated. The paint samples used were of the following:

- PITTSBURG Gloss Polymide Epoxy paint No. 97-1,
- OLYMPIC Poxolon 225 Blue Ice,
- PITTSBURG - Coal Tar Epoxy paint No. 97-640, and
- CAN - COAT Liquid plastic.

Two types of paint out of four showed very high resistance to electrical current while others showed high conductivity and high leakage. After considering the appropriateness for metallic surfaces, and past experience in using the product, an Epoxy paint (PITTSBURG - Coal Tar Epoxy paint No. 97-640)[1] was selected as the best insulation for the intended application.

For laboratory experiments and preliminary field testing applications it was decided to focus on water level fluctuations less than 3 *ft* (91 *cm*). Therefore, total length of capacitive sensor was made to be 91 *cm*. At the same time, it was necessary to decide upon a suitable diameter ratio for the concentric electrodes. Equation [2] provides the basic relationship between the radii ratio r_o/r_i and capacitance C. Other important factors considered at this level were the diameter of the outer tube compared with practical sizes of stilling wells and the intermediate spacing between cylinders required for service and cleaning purposes. By taking all these into consideration, aluminum pipes of diameter 12.7 *cm* and 10.2 *cm* (5 *in* and 4 *in*) were purchased.

After cutting into pieces of 91 *cm* (3 *ft*) in length, the tubes were cleaned thoroughly with a heavy duty sand blaster. Painting was done manually, using a roller type brush. This did not produce a very smooth surface, but the high viscosity of paint and the length of the tubes prevented the use of other possible painting methods such as spraying. Then the tubes were hung vertically to drain out any excess paint and for drying and curing of the Epoxy coat.

Two conductors were fixed together by using a pair of Plexiglass plates with properly spaced slots to hold the curved edges. A plastic threaded rod was passed through the center of the assembly and was tightened using two nuts (Fig. 7). A total of four such units were constructed and one was chosen for initial testing and calibration purposes.

The basic excitation circuit (Fig. 4) was connected and input, output voltage waveforms were observed. A digital circuit was designed to activate the sensor and measure the time delay t, which

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[1] Specified to describe the apparatus. No endorsement is made

reflected the submerged length of tube, l_2 (equation [8]). A Hardware Programming Language (Navabi, Swanson and Hill 1979) was used to verify the system operation before construction (AHPL program and outputs are shown in Appendix-C).

Potentiometer Sensor

This could be described as a modified buoyancy sensor where the rotation of the axle was used to cause a change in resistance of a variable resistor (potentiometer) thereby converting the water level fluctuations to changes in resistance. With the new data collection technique used in this development, it was possible to convert changes in resistance to digital format conveniently. It provided easy control and data acquisition capability with minimal additional circuitry.

Operation Description

The movement of the float caused a rotation of an axle to which a potentiometer (HELIPOT-10 turn variable resistor) was attached by means of a flexible coupling (Fig. 8). This converted the axle rotation to a change in resistance. Usually a variation in resistance is sensed electronically, with the use of an A/D converter. But, in this development, the capacitor charging principle was employed. It was the same technique which was used in the interface development for the capacitive type sensor described before. Therefore, the only operational change required for this unit was to keep the capacitor value, C, constant and let the resistance, R_p, vary according to the water level, changing the delay time imposed by capacitive charging (equation [10]). Measurement of delay time could be done with the same arrangement as described before, with slight modifications.

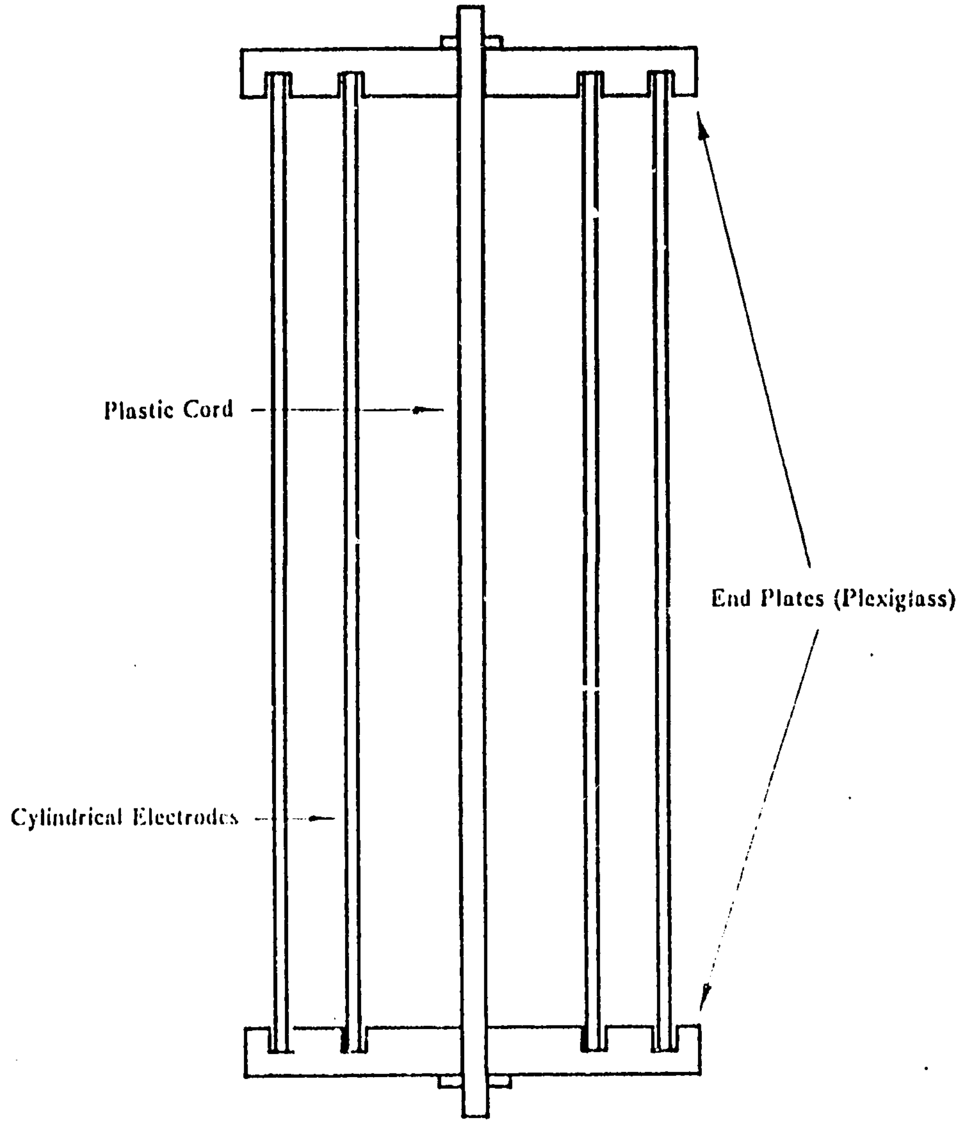

Figure 7. Assembled View of Capacitive Sensor

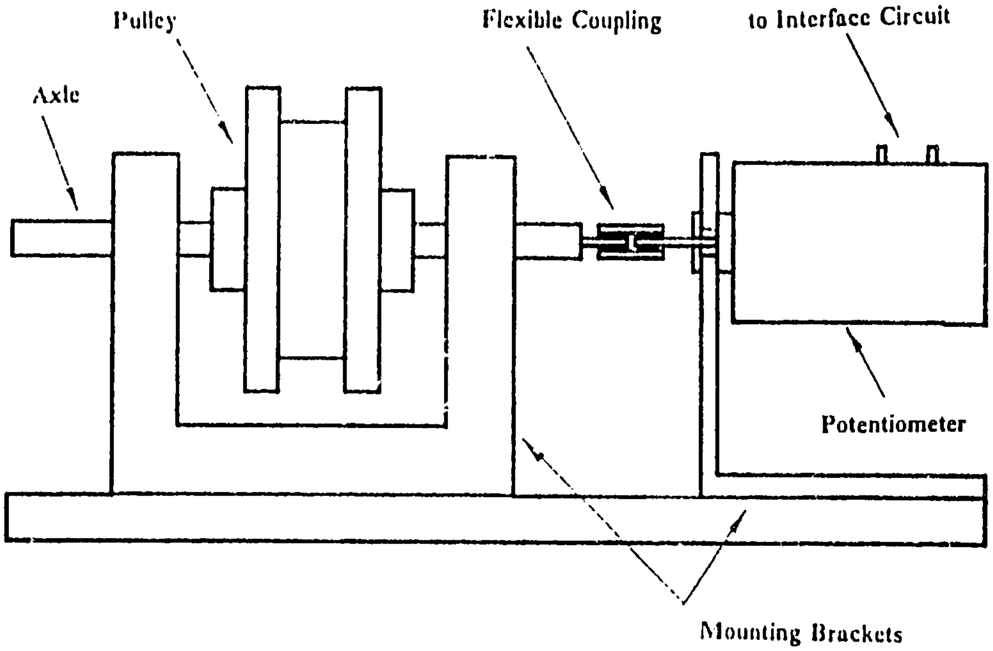

Figure 8. Potentiometer Sensor

Design and Construction

In order to achieve a significant resolution in the time reading, the resistance change per rotation had to be large. On the other hand, there was an upper limit on the maximum delay time imposed by the system capacity. Therefore, it was necessary to select proper values for the potentiometer and the constant capacitor to obtain the required resolution and to match the current circuit parameters such as clock frequency and threshold voltages. For this purpose, 5, 10, and 20 $k\Omega$ potentiometers and two types of capacitors were purchased. Both Polypropylene and Polyester - Foil capacitors were tested for their stability by keeping them fully excited for 3 weeks and measuring the charging time before and after. No noticeable changes were detected.

Theoretical analysis and experiments showed that 20 $k\Omega$ potentiometer connected in series with a $0.3\mu F$ capacitor provided suitable time delays for the complete range of application with the use of $500kHz$ clock (Table 1). The electrical circuit diagram of the potentiometer and capacitor arrangement is shown in Fig. 5. The next step was to design and construct a special float and weight mechanism for connecting the potentiometer. In this design, it was planned to utilized only 8 turns of the potentiometer to avoid non linearities or errors due to reaching upper and lower limits in the mechanical rotation of the axle. Pulley design was carried out by considering 1 m as the range for water level fluctuations. The complete assembly is shown in Fig. 8.

Table 1. Effect of Resistance and Clock Frequency on Counter Output.

Clock	Resistance	Capacitance	Counter Output	
kHz	*kΩ*	*μF*	*HEX*	*DECIMAL*
1000	5	0.3	255	597
	10	0.3	4A6	1190
	20	0.3	93C	2364
500	5	0.3	12A	298
	10	0.3	246	582
	20	0.3	49B	1179

Digital System Design

System Operation

Fig. 9 shows a schematic of the electronic circuits used during the testing. The excitation pulse of voltage V charged the capacitor C, formed by the sensor, through the resistor R. At the time of issuing the excitation pulse, a high frequency counter was also enabled. The output voltage V_o was sensed by the Schmitt trigger inverter U2, which in turn triggered the rest of the circuit when it reached the threshold level, disabling the counter. So, the time interval was recorded in the counter by counting a high frequency clock, during the the interval between issuing the pulse and output voltage reaching the threshold level of the Schmitt trigger input. Within the next two clock pulses, the counter output was loaded to a latch and hexadecimal display unit and the system was made available for the next cycle of measurement, allowing continuous display of data. The circuit was built on a development system bread board and all excitation and clock pulses were generated on board, using timers and crystal oscillators.

This circuit was used in preliminary testing and proved successful. Certain modifications were made to minimize display fluctuations. Even though this provided necessary sensor output, data recording was carried out manually. A fully automatic data logging system was developed, based on the same principle of operation, as described below.

As could be seen from the theoretical analysis, one of the major advantages of the developed sensor was that it converted water level change to a change in delay time, which could be easily measured using digital techniques. In addition to the measurement of time, the intended control system was required to issue excitation pulses to the sensor. A microprocessor based (HD64180) data logger-controller board (VITRAX Microcontroller version IX)[2] was purchased. It consisted of a HD64180 microprocessor, an EPROM which contained BASIC (VITRAX BASIC version 3.5) system installed in it, and additional RAM space. It also had the additional features of having 24 programmable Digital I/O lines controlled through a Peripheral Interface Adapter (PIA), 56k-byte memory capacity, on-board EPROM programmer, two 16-bit programmable counter/timers, 4 external interrupts, centronics parallel printer interface, two RS-232 serial ports, and other optional facilities such as analog to digital converter (Sintec 1988).

Upon examination of the original hardware supplied, it was noticed that the power consumption was much higher than what is appropriate for a field unit. Therefore, all integrated circuits were changed to their CMOS versions in order to minimize current consumption. Furthermore, additional ICs mounted for optional tasks were completely removed.

The data logger system was operating on an EPROM based BASIC system A program was written in BASIC, (Appendix A) to control the sensor and store data. At a later stage, it was decided to change the control from BASIC to Modula-2 (Wirth 1985) for several reasons, such as easy input-output control and faster execution speed. A Modula-2 program was written by making the necessary additions and modifications to an existing system on a different data logger setup. This change made it possible to utilize the low power consumption mode (sleep mode) available in HD64180 processor without any difficulty. With all these software and hardware changes it was possible to reduce the average current consumption from its listed value of 175 mA to 12.5 mA.

Interface Circuit

An interface circuit was designed with an external clock generator, 16-bit binary counter, and additional logic gates. Control pulses were issued by the microprocessor through the on-board PIA

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[2] Specified to describe the apparatus. No endorsement is made

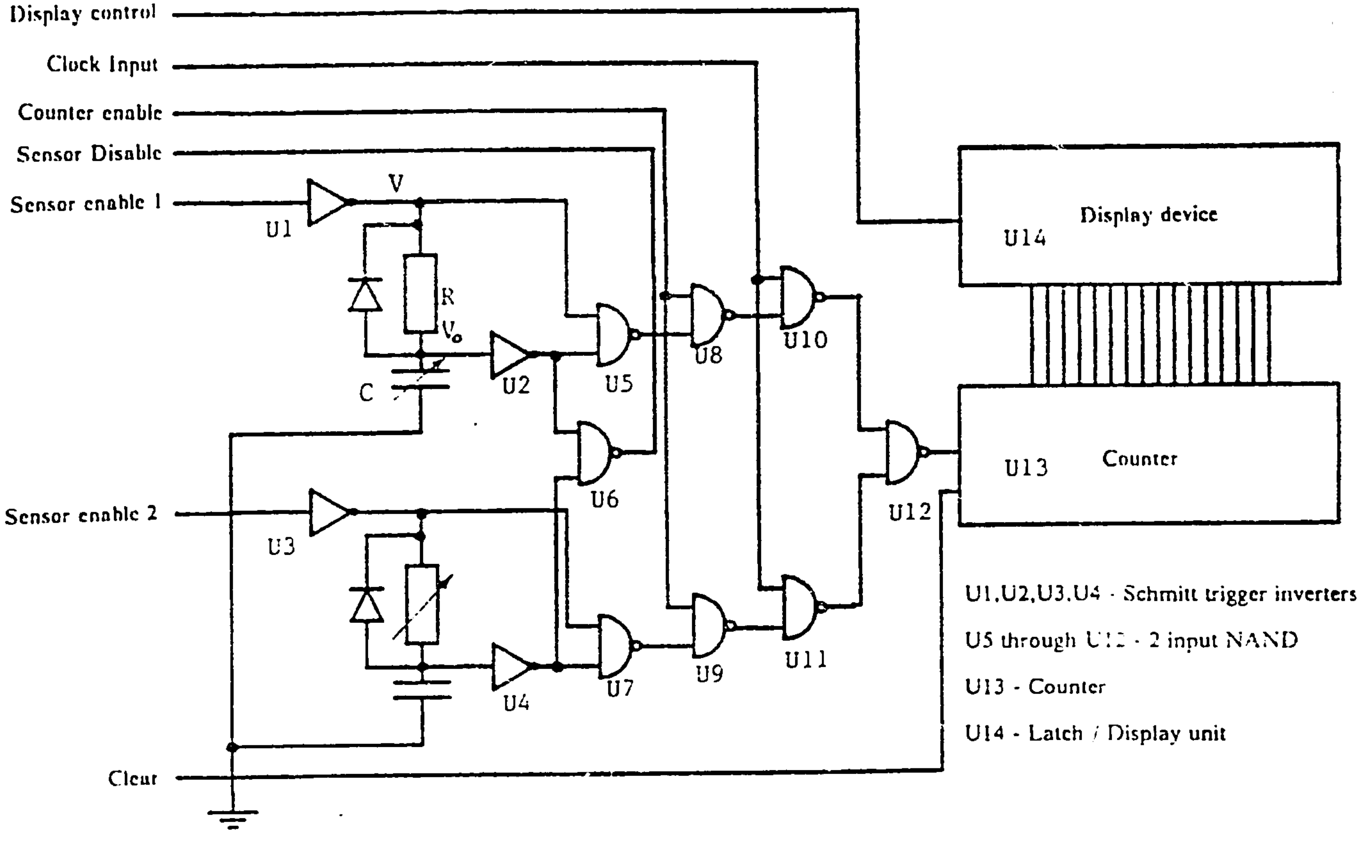

Figure 9. Schematic Diagram of Excitation Circuit

and necessary logic circuits were designed to carry out counter enable/disable tasks in synchronization with processor operations. Counter output (12 bits) was read into memory through PIA ports at each excitation (Fig. 10).

This gave rise to two additional problems. First, it increased the overall power consumption of the system and second, it required the addition of a separate printed circuit board attached to the data logger. Both these factors were not considered favorable for field operations. Therefore, it was decided to modify the data logging operation by utilizing the internal counter of the 64180 microprocessor, which was activated by the system clock. This drastically reduced the interface circuit to one hex Schmitt trigger inverter unit for controlling both sensors. After careful examination, the inverter was installed on the microprocessor board itself, making use of an unused IC space. Connections to the PIA port and sensors were made using wire wrapped links. A schematic diagram is shown in Fig. 11. The developed system was tested for its proper operation and proved successful.

All software programs were written in Modula-2. The system carried out the following steps during one cycle of operation:

1. stored year, date, and hour every hour on the hour,
2. updated its internal 'real time' clock every 10 *ms*,
3. responded instantly to internal or external interrupts,
4. activated the sensors every 10 minutes in the following sequence:
    a. issued necessary control commands for proper resetting of PIA ports,
    b. loaded internal counter to its high value (FFFF FFFF Hex),

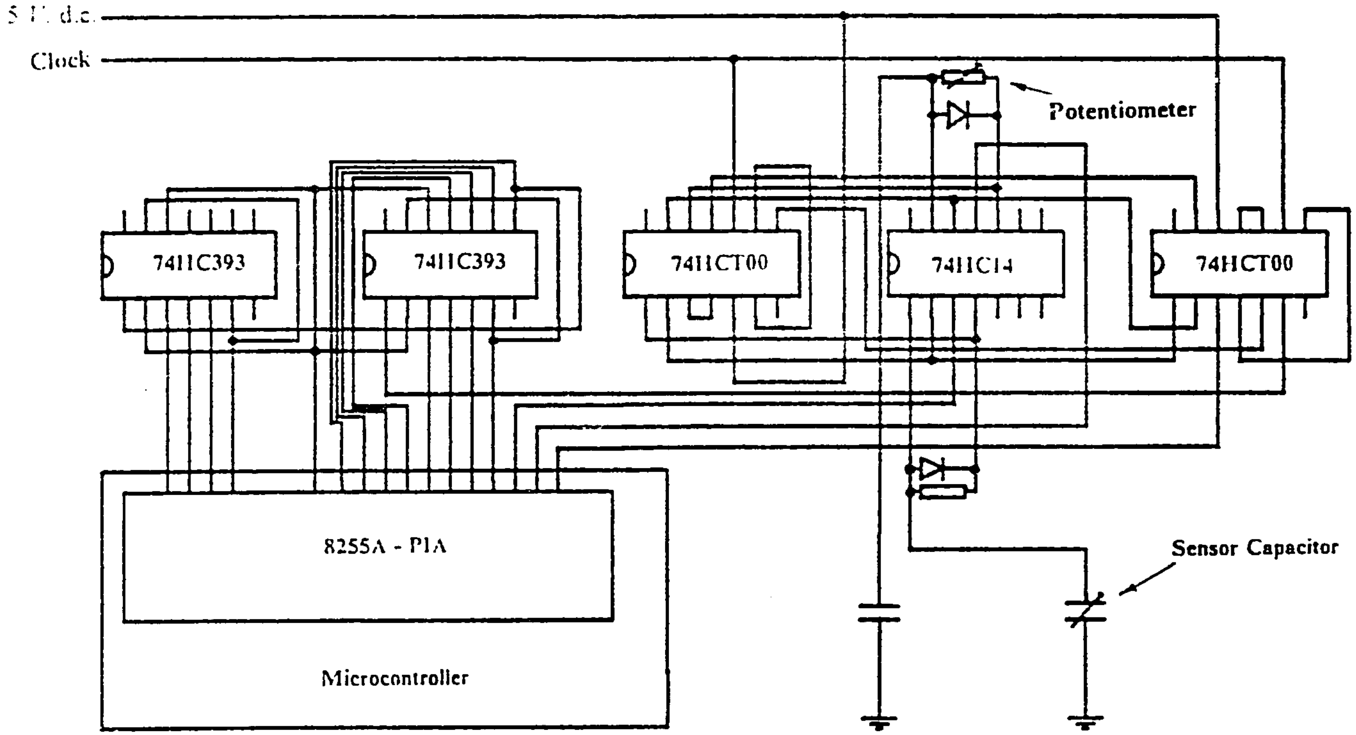

Figure 10. Circuit Diagram - Interface Circuit

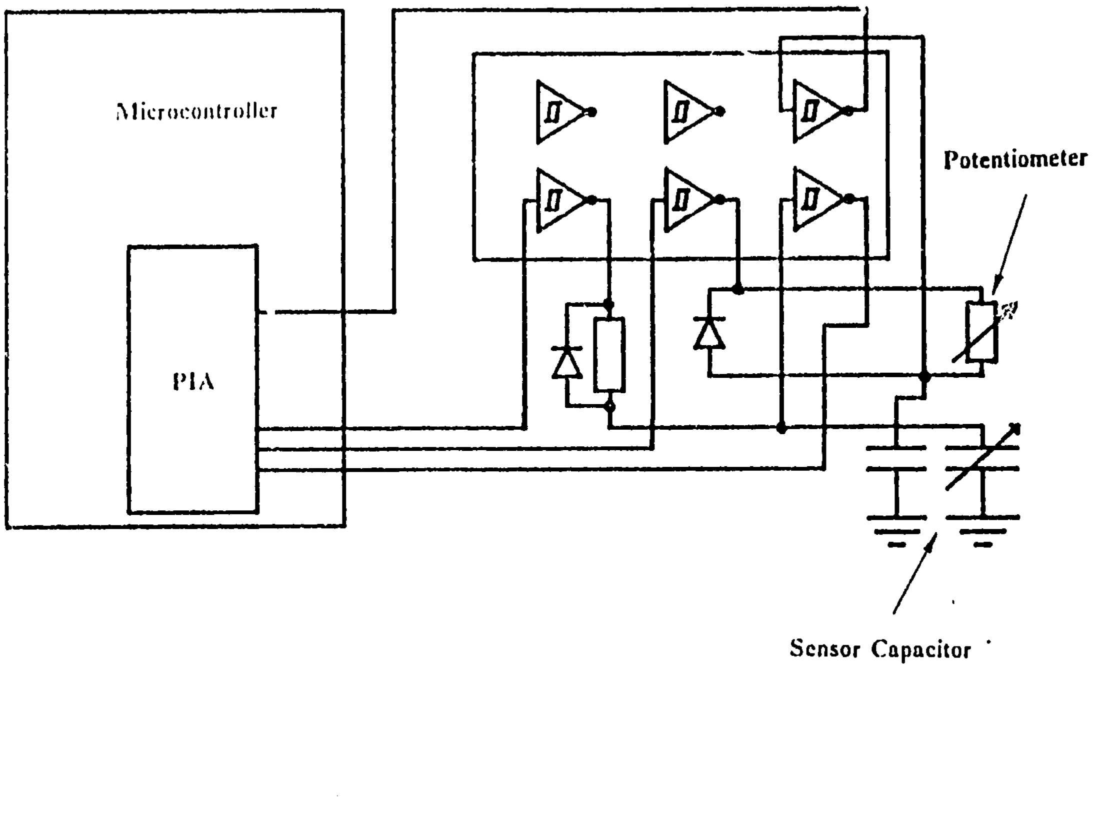

Figure 11. Circuit Diagram - Modified Interface Circuit

c. issued an excitation pulse to the sensor (capacitive type) through the PIA,

d. started decrementing its counter,

e. proceeded until the sensor capacitor was charged to threshold level and stopped decrementing upon sensing it.

f. reset the excitation pulse to ground level,

g. read the internal counter and obtained the count which represents the water level, and stored it temporarily,

h. repeated steps (b) through (g) 11 times,

i. computed the average and sum of squares of the last 10 data points collected (counts), (this scheme of excluding the first data point was suggested to eliminate possible error due to charges collected during the time interval between excitations)

j. if the residual sum of squares (SS) was less than a pre-specified value, the logger stored the average,

k. if SS was higher, which showed higher variation among data points, repeated steps (b) through (i) until a satisfactory SS was obtained,

l. if SS was unsatisfactory for three (3) such trials, terminated excitation and stored the average of 30 data points,

m. repeated steps (a) through (l) for the other sensor (potentiometer) and returned to sleep mode, and

5. carried out down loading of a required number of data points from storage when requested on RS-232 serial lines.

A listing of the Modula-2 program is supplied in Appendix B.

Testing

Tests were carried out with the capacitor unit connected to the excitation and control system (without the use of the microcontroller), to investigate the reliability of the digital circuit and behavior of the sensor. The circuit was triggered manually and data were recorded from the attached display device. During these preliminary tests, the following problems were encountered and were corrected.

It was noticed that the display was unstable and was fluctuating around a certain value when the water level was constant. It was also observed that the fluctuations were wide at certain sampling frequencies and negligibly small at other frequencies. This was found to be due to the difference between the sampling frequency and the 60 *Hz* power supply frequency. Whenever the sampling frequency was set to 60 *Hz* or a multiple of 60, this fluctuation was minimized. The use of a very high sampling frequency showed more consistent results. But this approach was not recommended because a higher frequency excitation had the tendency to adversely influence the system by lowering the overall leakage resistance.

Another requirement was to have a low power consumption so that prolonged field use was possible. Therefore, it was decided to use CMOS integrated circuits which consume less power than TTL types. This considerably lowered the maximum operating frequency as CMOS devices do not operate at very high frequencies. Another factor contributed to the determination of the clock frequency was the necessary resolution. A summary of investigations on various combinations of charging resistors and clock frequencies is given in Table 2. After these studies, it was decided to proceed testing with 500 kHz clock and 100 $k\Omega$ charging resistor R, a combination which provided a resolution of about 5 counts per 3 mm depth of water. It was decided that this resolution was quite adequate to establish sensor characteristics. Sampling rate was set to be about 1 Hz which allowed convenient reading of the display even when it was fluctuating.

Several tests were carried out to examine the operation of the sensor for rising and falling water levels. For these preliminary tests, the water level change was achieved by siphoning water in and out of a plastic container. This setup limited the total level change to about 30 *cm*. Readings were recorded at each time for both increasing and decreasing water levels, with the use of a calibrated water column.

Test Stand Design

Even though it was possible to carry out preliminary tests and establish basic relationships on the actual behavior of the sensor, it was necessary to be able to compare each device with another standard water level sensing mechanism for the purpose of calibration. Laboratory tests described before were performed using two separate plastic containers (30 *cm* diameter and 30 *cm* height) and siphoning water in and out each time. With this setup it was impossible to investigate the full operating range of the sensor.

A test stand was built with three interconnected PVC sewer pipes (diameter 18 *cm*). All bottom ends were sealed with PVC caps and the pipes were interconnected using TYGON tubes (diameter 2 *cm*) at a height of 30 *cm* from the bottom. Please see Fig. 12 for details. In this way, it was possible to achieve the same water level changes in all three pipes.

Table 2. Effect of Charging Resistor and Clock Frequency on Counter Output at a Constant Water Level.

Clock Frequency *kHz*	Charging Resistor *kΩ*	Counter Output *HEX*	 *DECIMAL*
200	150	0DE	222
	100	097	151
500	200	42B	1067
	100	19C	412
	50	0C4	196
1000	100	34B	843

Water was poured into one pipe through a funnel and an outlet was connected at 30 *cm* level for decreasing the water level whenever required. The total height of the pipes was 1.5 *m* and they were rigidly secured vertically with a wooden frame.

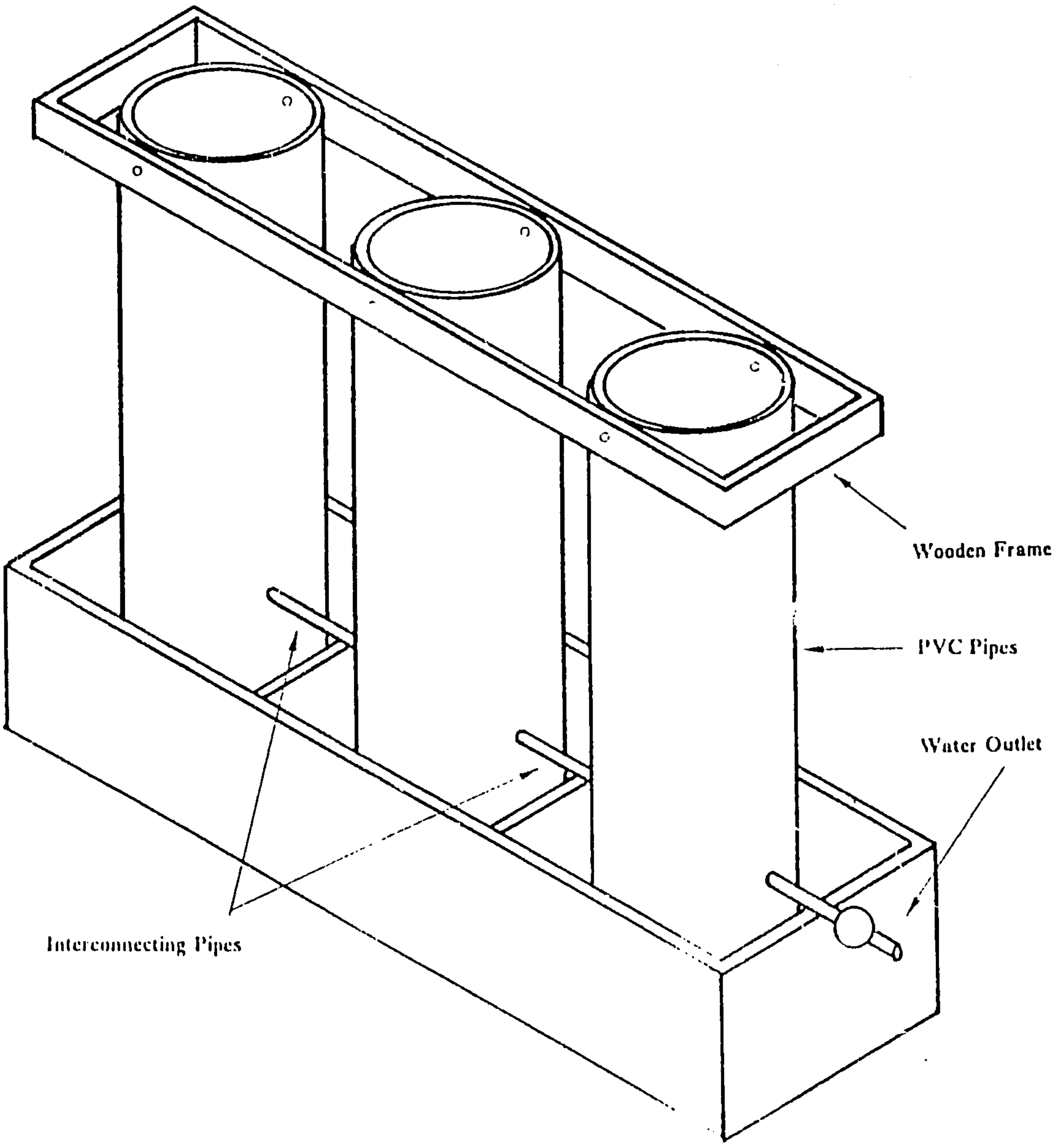

Figure 12. Test Stand for Calibration of Prototypes

Experimental Procedure and Analysis of Data

Calibration of Capacitive Sensor

For the purposes of calibration and development of required data logging facilities, tests were carried out in the following order. First, a capacitive type sensor was installed in one of the pipes of the test stand. A commercially available pressure sensor (Sierra - Misco Model 5050LL-PTF) and a conventional point gage (for calibrating the pressure sensor) were installed in the other two pipes (Fig. 13). Characteristics of the pressure transducer (Sierra-Misco 1987) and the point gage are separately listed below.

Pressure Transducer

- Listed accuracy: ± 0.5% of the transducer range (equivalent to ± 0.06 *ft* for the 12.0 *ft* range).
- Range of operation: 0 - 3.61 *m*
- Output: 0 - 5 *V*. d.c.

- Output display device: KEITHLEY - Model 191 Digital Multimeter.

- Range: 0 - ± 20 *V*.

Point Gage

- Resolution: ± 0.3 *mm*

- Range: 0 - 0.6 *m*

Capacitor excitation and measurement of delay time was done by manually triggering the control circuit as before. The system in Fig. 8 was used in these experiments. Displayed output, which was in hexadecimal (*HEX*), was recorded at each time of excitation. Continuous application of a d.c. voltage to capacitor plates showed a drift in the reading for time delay. This was suspected to be due to effects of electrolysis and polarization of molecules and was assumed to be dependant on the chemical composition of water. To reduce such errors, the control circuit was designed so that the voltage pulse was issued only at the time of measurement and all other times, the sensor electrodes were kept short circuited and at ground potential. This operating scheme also helped to minimize power consumption. Water level of all the pipes were simultaneously changed by adding water to one pipe through the funnel. The following items were recorded for further investigations and statistical analysis:

1. Time of the day, of adding or draining out water from the system,

2. Amount of water added or drained out at each time,

3. Time of the day of reading sensors. (items 1 and 3 were recorded to investigate the effect of settling time on reading),

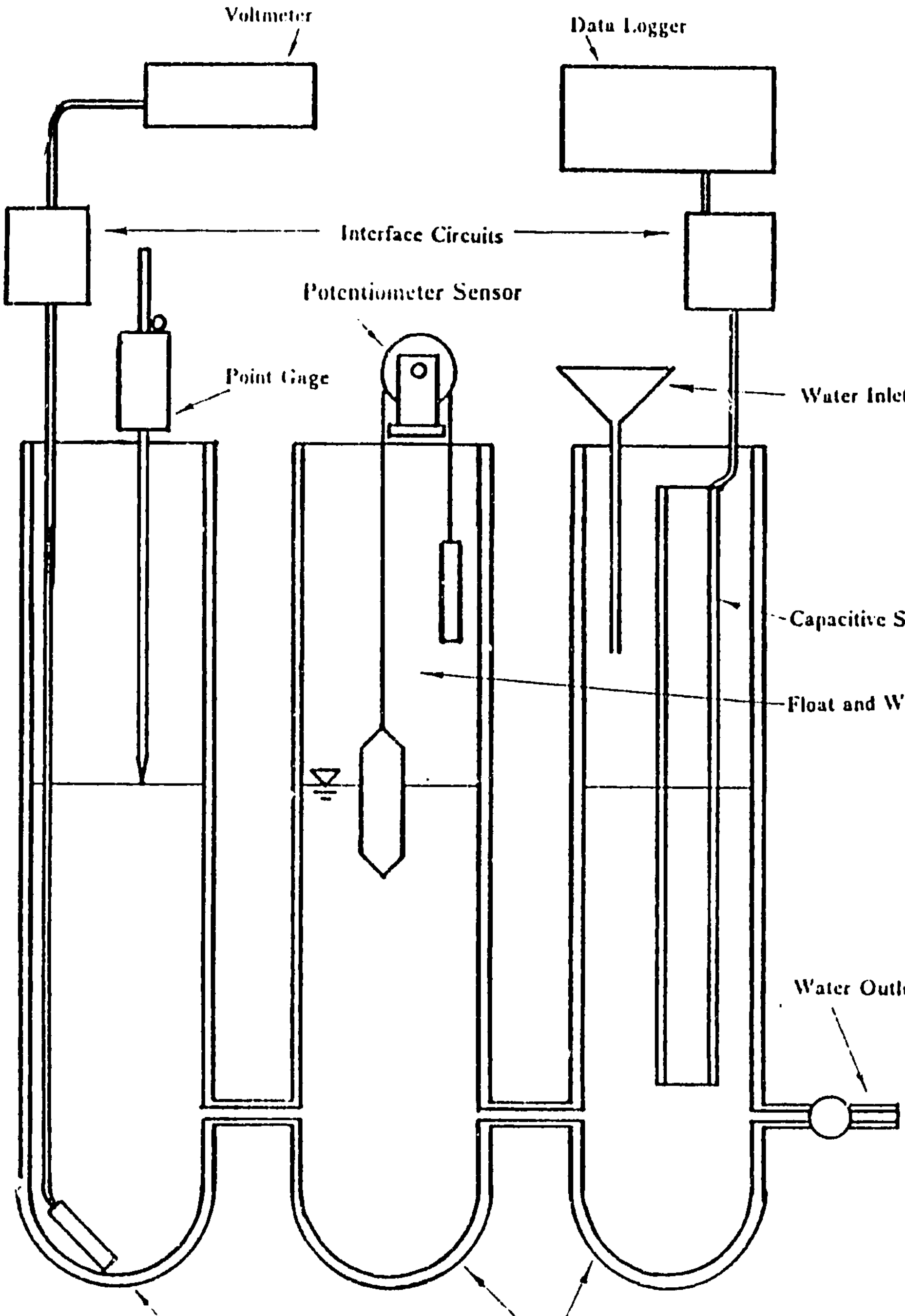

Figure 13. Measuring Equipment Installed on the Test Stand

4. Pressure sensor reading (V_p),

5. Point gage indication (mm), and

6. Capacitive sensor output (HEX).

As described before, the observation for the time delay of the capacitive sensor was obtained by the display of a counter output. Even though it was a certain number of pulses which represented a time delay, no attempt was made to convert the number of pulses to time units because the direct use of counts simplified the data processing and caused no additional errors. So, the number of pulses recorded from the capacitive sensor was directly used in the analysis and was denoted by the variable $CCOUNT$. Pressure sensor output obtained by a five and a half digit digital multimeter, specified above, was denoted by V_p.

Analysis of Data

Because the primary objective of data analysis was to develop a relationship between the new water level sensor and standard device output, a simple linear regression was suggested as the best approach according to the theoretical relationships developed before. Statistical Analysis System Version 5.16 (SAS v. 5.16) was used in these analysis (SAS Institute 1979). Simple linear regression process derived coefficients (intercept and slope) to relate the dependant variable to the independent variable through a linear equation. In addition to these coefficients, it also provided a measure of error incorporated in the model (standard error) and a measure of agreement between observed data points and model predicted data (R^2).

Both these factors were given consideration because the objectives were to investigate whether the actual behavior was linear in accordance with the theory and to find the degree of accuracy with which water levels could be measured by the new sensor.

Even though a value of 0.999 for R^2 was a very satisfactory indication for a linear fit, it was decided to examine further to establish exact sensor characteristics by obtaining a plot of residuals with predicted water levels. The plot indicated the distribution of the difference between the measured water level (standard sensor) and predicted water level (capacitive/potentiometer data). Observations made using the residual plot were immensely helpful in detecting variations in sensor characteristics which were undetectable otherwise.

Analysis of the data showed that the pressure transducer was linear with both increasing and decreasing water levels. The pressure transducer voltage - stage data were fit with a linear model by regression. Resulted R^2 was 0.9999 and the standard error was 1.8 *mm* (28 observations) when V_p was used to predict stage in meters as measured by the point gage. The model, equation [13], was:

$$Stage = 2.456\ V_p - 1.848. \qquad [13]$$

Therefore, the pressure sensor was considered as the reference device to calibrate the new prototype. The pressure sensor output V_p was directly converted to stage according to the results of previous calibration and was denoted by L in the rest of the analysis. All statistical analysis were carried out between capacitor data ($CCOUNT$) and pressure transducer data (L). A simple linear regression (equation [14]) between the pressure sensor data and the capacitive sensor data resulted in an R^2 of 0.9984 and a standard error of 0.931 *cm*.

$$L = A_1 + A_2\,CCOUNT \qquad [14]$$

On further examination of the results, a prominent pattern in the residuals was observed (Fig. 14). It was previously shown that, theoretically, the relationship between L and delay time $CCOUNT$ is linear. But the residual pattern indicated the existence of an outside effect which changed the theoretically expected behavior. It was hypothesized that this interference was from the 60 *Hz* power supply frequency and resistor - capacitor combinations reaching electrical resonance states as they are gradually changed with varying water level. This assumption was primarily based on the peculiar pattern of residuals which resembled a sinusoid.

After including data for both increasing and decreasing water levels, the residuals showed a pattern which highlighted the portion for decreasing water levels (Fig. 15). The reason for this difference between the data from rising and falling water levels was that the readings for the falling water levels needed to have been taken more slowly than they were. The first point in the data for falling water levels was taken after sufficient delay, and this point was not different from the rising data, as can be seen in Fig. 15. After recording the first point, it was incorrectly decided that data could be collected at a higher speed. Allowance of more time after each decrement of water level was expected to improve the response. This was not considered as an obstacle for the system development because, in this particular application of irrigation water scheduling, the time span considered is very long and the data collection rate can be lowered enough so that such errors are minimized. For all the other experiments, the speed of measurement was set to be 5 min after each increment of water level and 10 min after each decrement of water level.

To further investigate the hypothesis that residual pattern is caused by stray voltages, a series of experiments were planned. As a first step, repeatability of the experiment was tested by carrying out the same procedure again without changing any of the critical parameters. In order to minimize the previously observed discrepancy between the readings for increasing and decreasing water levels, 5 min settling time was allowed before taking the reading at each decrement of water level. The residual pattern is shown in Fig. 16. This pattern and other related statistical parameters clearly indicate that the behavior of sensor is stable and it shows similar characteristics repeatedly.

The next step was to change possible sources of stray electric fields and observe the effect. Two possible sources suspected in this search were 60 *Hz* power supply and high frequency clock signals generated on the control circuit itself. The power supply for the capacitor excitation circuit was

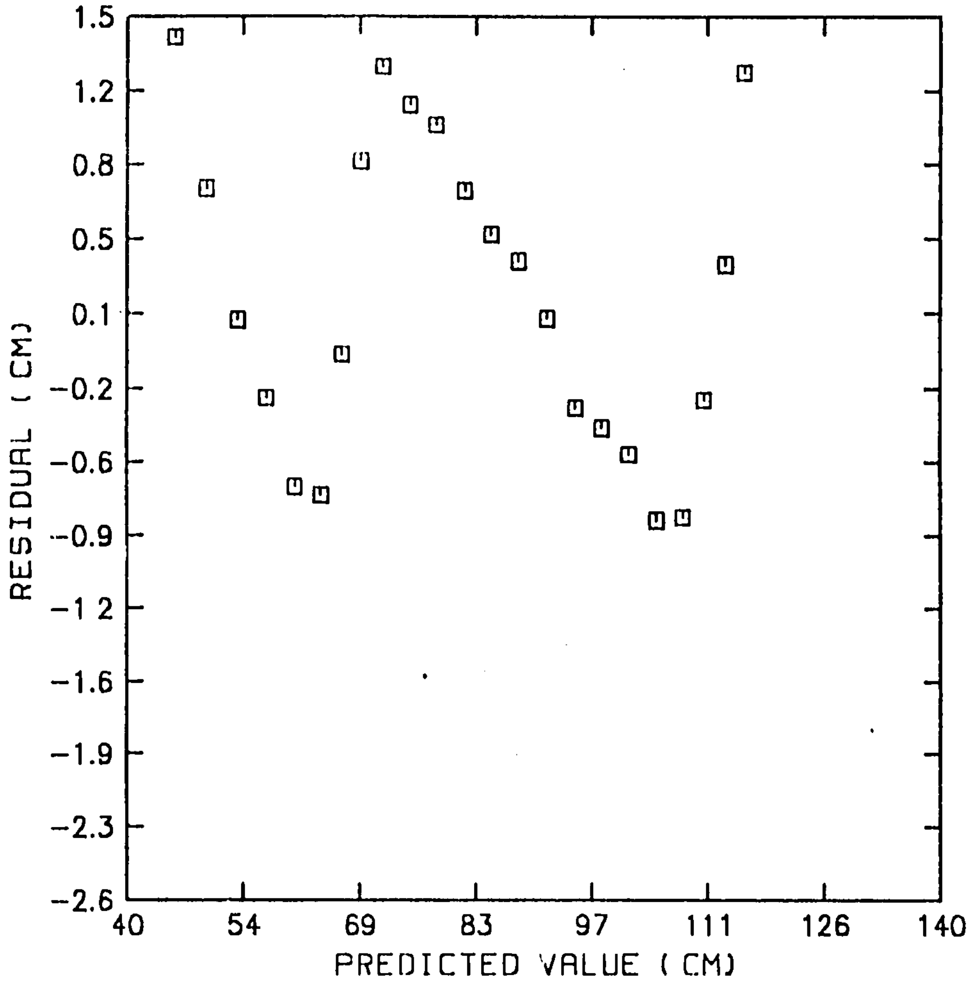

Figure 14. Residual Pattern - Increasing Water Levels Only

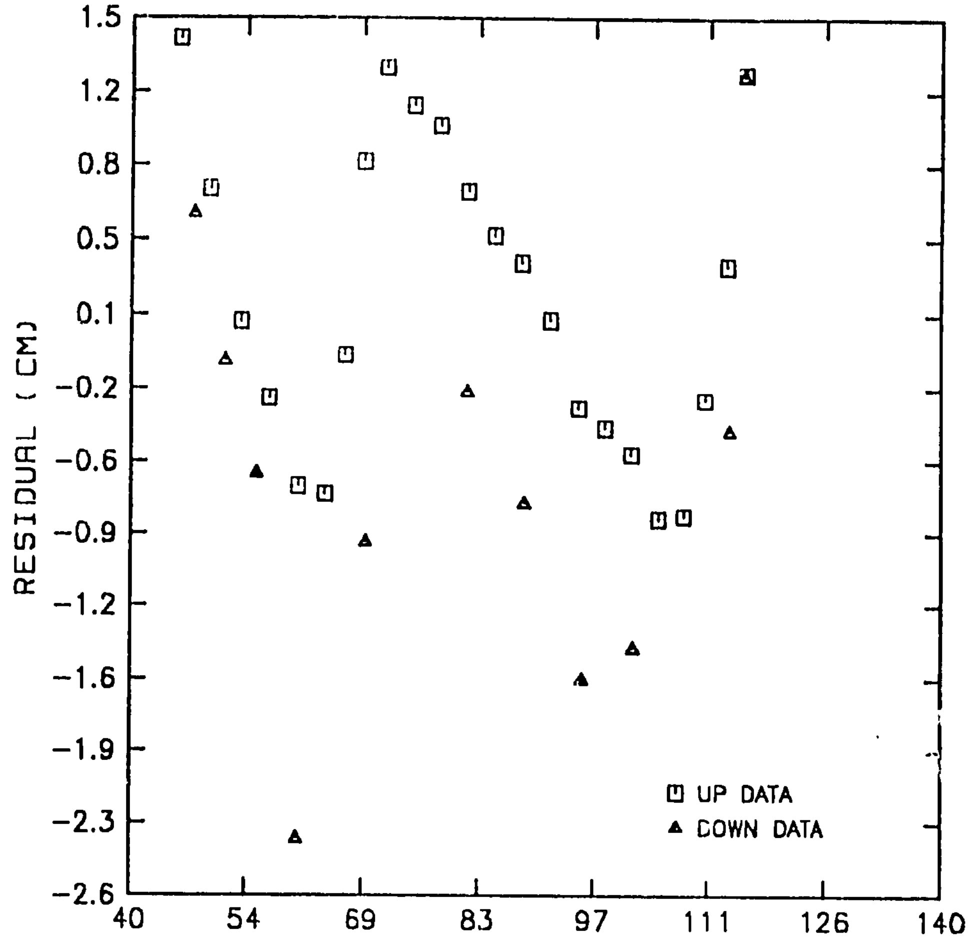

Figure 15. Residual Pattern - Increasing and Decreasing Water Levels

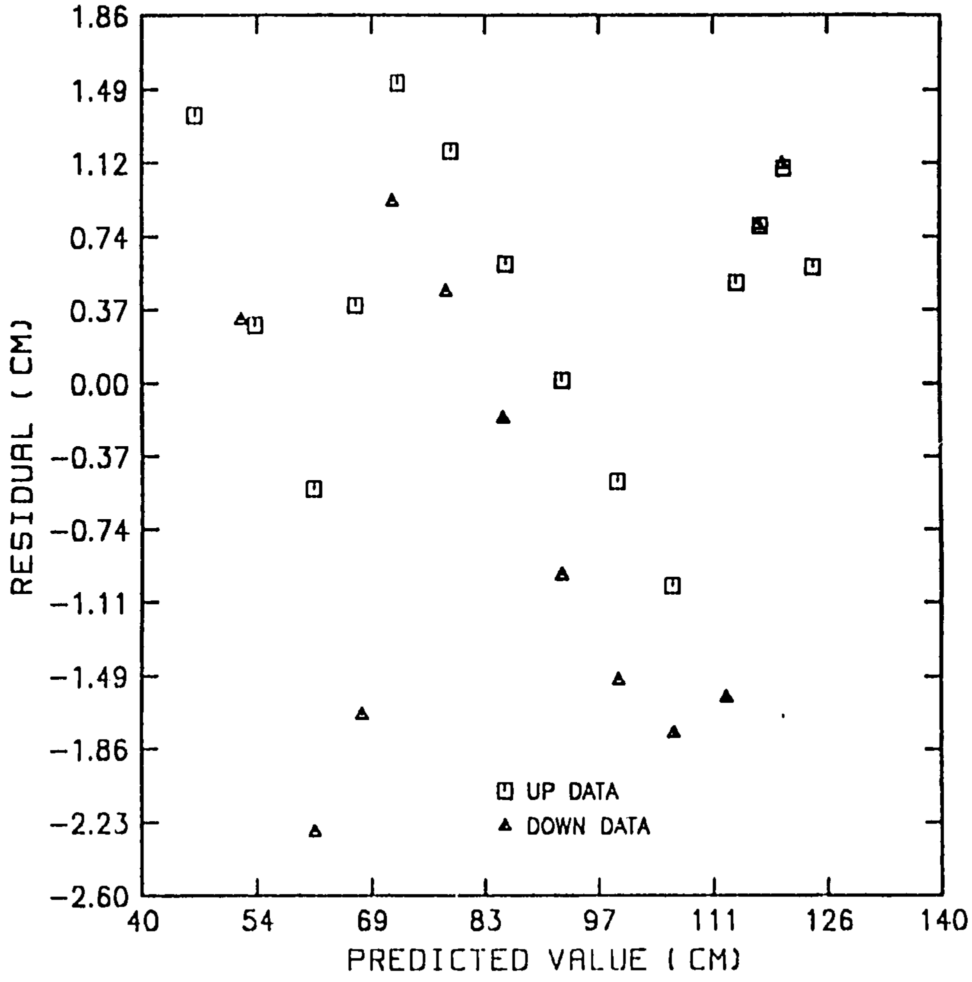

Figure 16. Residual Pattern - Increased Settling Time for Decreasing Water Levels

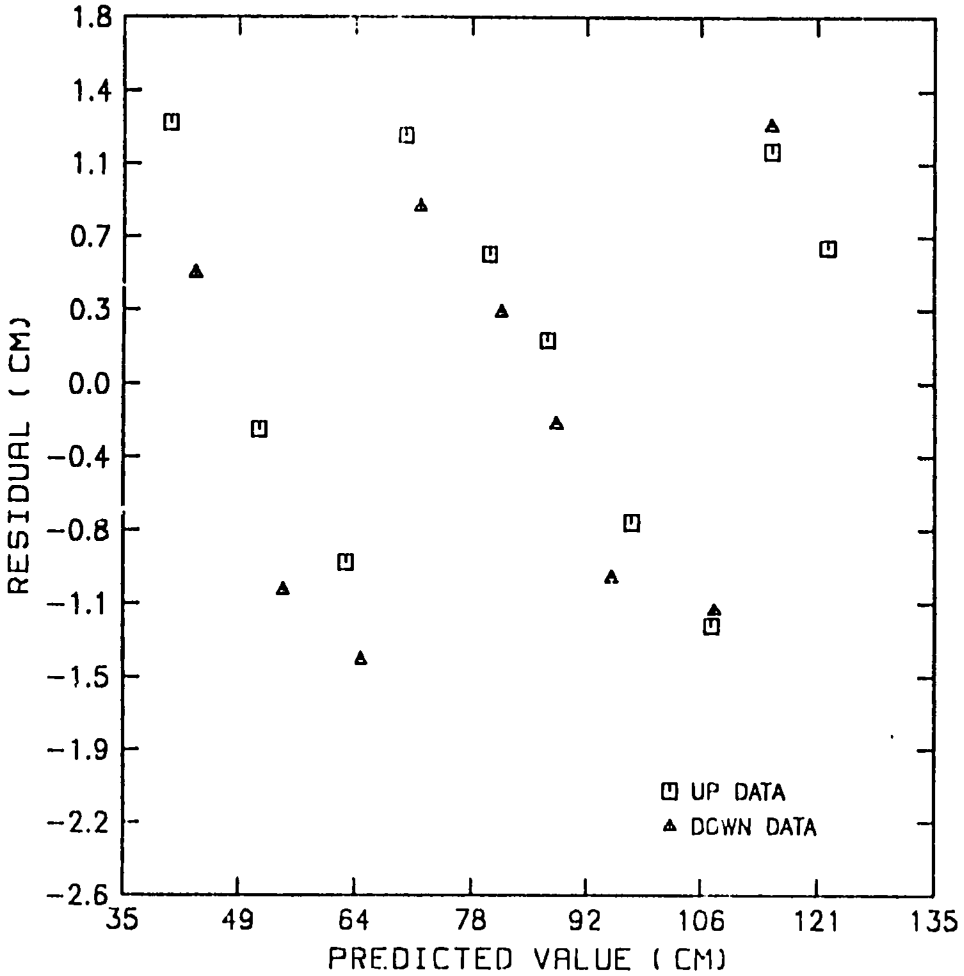

Figure 17. Residual Pattern - Control Circuit Activated by a D.C. Source

changed form a.c-d.c converter/regulator to a separate regulated d.c battery supply. This change was made to eliminate 60 *Hz* ripple voltage which is an inherent characteristic of a.c.-d.c. converters. The same experiment was carried out with this change and data was analyzed according to the model in equation [14]. The resulting residual distribution is shown in Fig. 17.

- R^2 obtained = 0.9986

- Standard error = ± 0.983 *cm*

Because this distribution showed the same pattern it was assumed that the source of the pattern was not the power supply. Another hypothesis mentioned above was that the observed effect is due to another high frequency signal possibly generated by the control and excitation circuit itself. In order to isolate the possible source of error, another test was carried out with an additional screen around the pipe carrying the capacitive sensor. Screening was done by wrapping a wire mesh (2.5*mm* x 2.5*mm*) around it and connecting to ground potential. This was expected to minimize any stray electric fields due to all outside sources. After analyzing data, it was observed that the alteration has caused no significant changes to the residual pattern or the operation of the sensor.

These experiments and related analysis confirmed that the effect is not due to noise emitted either from the power supply or from outside sources. Another test designed to investigate whether it is due to high frequency resonance of the connecting cable and the capacitor assembly proved that use of the cable improves the performance by guarding against existing stray signals. Therefore, it was decided to continue using the cable for the connections between sensors and control circuits. At the same time, an interface circuit (Fig. 10) was designed and constructed to automate the data recording, with the help of a computer. A microprocessor based data logger board (VITRAX MICROCONTROLLER version IX) was used to control the capacitor unit. Due to this change, the additional circuitry previously required could be greatly reduced. Software was developed using the BASIC system already installed in the data logger (VITRAX BASIC version 3.5). Another advantage was the easy operation and elimination of human error in reading data. To minimize errors due to intermittent fluctuations of reading, 10 observations were taken at each time and average value for counts was used for further analysis ($CCOUNT$). At a later stage, the circuit was further simplified to minimize power consumption (Fig. 11).

This change of control circuit was supposed to cause a change in the overall response of the system if the observed behavior was due to some resonance effect of the inductances and capacitances in the bread board and additional wiring. But, the results of tests, shown in Fig. 18, conducted after the use of data logger board indicate that there was no effect of the properties of the circuit towards changing the residual pattern but it did provide more consistent data both in increasing and decreasing phases. This improvement was due to the uniformly spaced observations and averaging to get the final response. The system clock frequency was changed in the next experiment to investigate its effect on the residual pattern. It was increased to $800kHz$ and decreased to $200kHz$ in two consecutive tests. But, it could be seen that either an increase or a decrease in clock frequency had no effect on the observed pattern. Charging resistor R was also changed to $150k\Omega$ from its previous value of $100k\Omega$ in a separate experiment to check the effect of the time constant RC on the sensor performance.

After this series of experiments and statistical analysis explained above, it was confirmed that the observed residual pattern was not due to any stray effect or electrical resonance effect. Based on those observations, it could be hypothesized that the physical geometry of the Aluminum tubes itself contributes to the unexpected behavior. During all the above tests, the same pair of tubes was used to preserve the consistency of the system variables. The next experiment was carried out with a different pair of tubes of the same dimensions. The microcontroller board and the screened cable were used because they have proven to be the best combination for the data acquisition system. Recorded data were analyzed according to the same model (equation [8]) and results are shown below. The residual pattern is shown in Fig. 19.

- $R^2 = 0.9992$

- Standard error = ± 0.77 *cm*

This showed a completely different pattern compared to previous residual distributions, while indicating a fairly linear fit. Residual patterns for two other sensors, resulting from the same test and analysis, are shown in Fig. 20 and Fig. 21. From these observations, it was obvious that the source of error, which had been searched for, was the irregularities in electrical or geometrical properties of the sensor. In order to establish a theoretical explanation, another analysis was made on the effect of these variables on delay time.

There are two properties which may cause such irregularities and therefore, were of major concern. The time delay measured is dependent on the capacitance (C) and the charging resistance (R). But, it is also dependent on the leakage resistance between electrodes (equation [7]). Irregularities in capacitance along the axis of the tubes may also be caused by non uniform diameter ratios of the pair of tubes.

To study the effect of non uniformities in tube diameter, equation [6] was partially differentiated with respect to the radii ratio r ($r = r_o/r_i$). To simplify the analysis, the effect of the portion of tube in air was neglected by assuming $\epsilon_1 = 0$. This resulted the following relationship between the change in delay time δt caused by a minute change in diameter ratio δr.

$$\delta t = -\frac{\delta r}{r \ln r^2} R \ln \left[1 - \frac{V_T}{V} \right] 2\pi \epsilon_2 l_2 \qquad [15]$$

Using this relationship, it was found that the percentage change in delay time due to a 1% change in diameter ratio r was 4.48% for the presently used combination of cylinders with diameters 12.7*cm* and 10.2*cm*. This highlighted the affect of the precision of the tube diameter on the final accuracy of the observed reading.

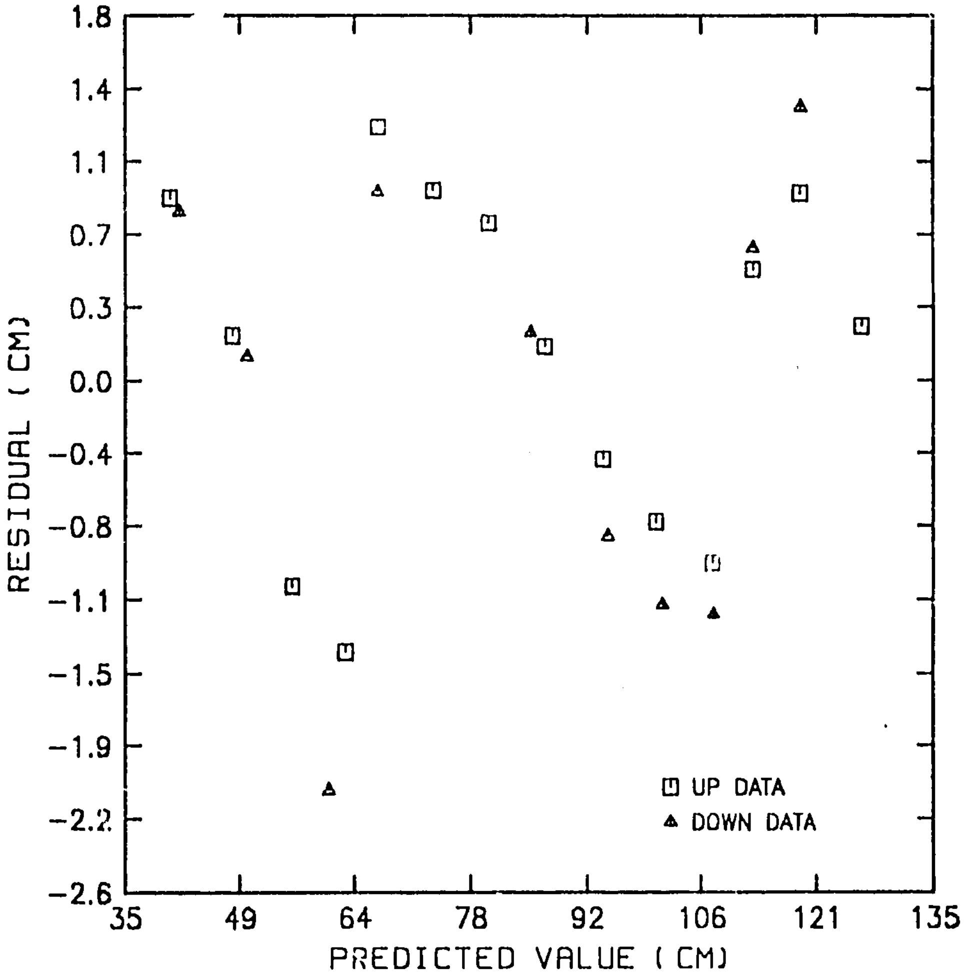

Figure 18. Residual Pattern - After the Use of Microcontroller Device

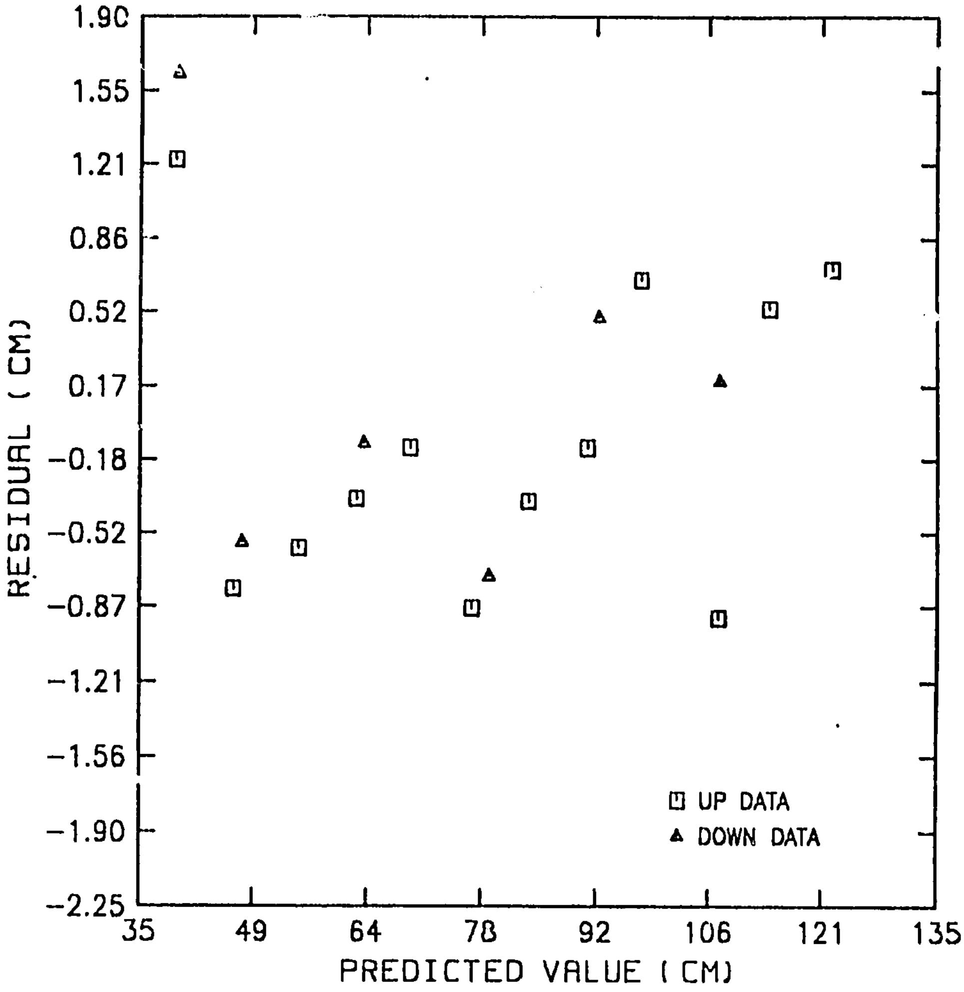

Figure 19. Residual Pattern - Second Pair of Tubes

From the equation [7] it could be seen that the nonuniformities in the leakage resistance may be another cause for the observed behavior. Changes in leakage resistance eventually caused a change in equivalent resistance for charging. (equation [8]) The degree of the affect could again be estimated by differentiating equation [8] with respect to R_{eq},

$$\delta t = -C \ln\left[1 - \frac{V_t}{V}\right]\delta R_{eq}. \qquad [16]$$

Equation, [16], was used to calculate the percentage change in delay time δt due to a small change in charging resistance δR_{eq}, which was found to be a 1% change in δt for a 1% change in R_{eq}. Based on these analysis, it was possible to conclude that the observed residual pattern was caused by either of the properties discussed above.

Upon observation, it was noticed that the thickness of insulating paint coating was not uniform. The leakage resistance discussed above consisted of resistances across the thin layer of paint at each level of tubes. Therefore, there was a possibility that the variation had been caused by uneven paint thickness. Further tests were necessary to correctly identify the source of error whether it was the nonuniformities in leakage resistance or the diameter ratio along the axis.

Upon examination of the tubes used for sensors, it was observed that there were some dents caused in handling and previous use. In the preliminary design stage the effect of these were neglected because the primary goal was to establish the basic principles and overall response of the unit. Because the sensor excitation and data acquisition system were now developed to provide sufficiently accurate data to highlight such irregularities, further steps were necessary to develop a sensor ith a more uniform response

Based on the results discussed above, several tests were planned as an attempt to find a better design for the capacitive type sensor. First, a pair of tubes with minimum dents and irregularities was selected from the four units constructed and tested before. The residual pattern obtained from the test carried out with this particular set showed a more uniform variation compared to those of

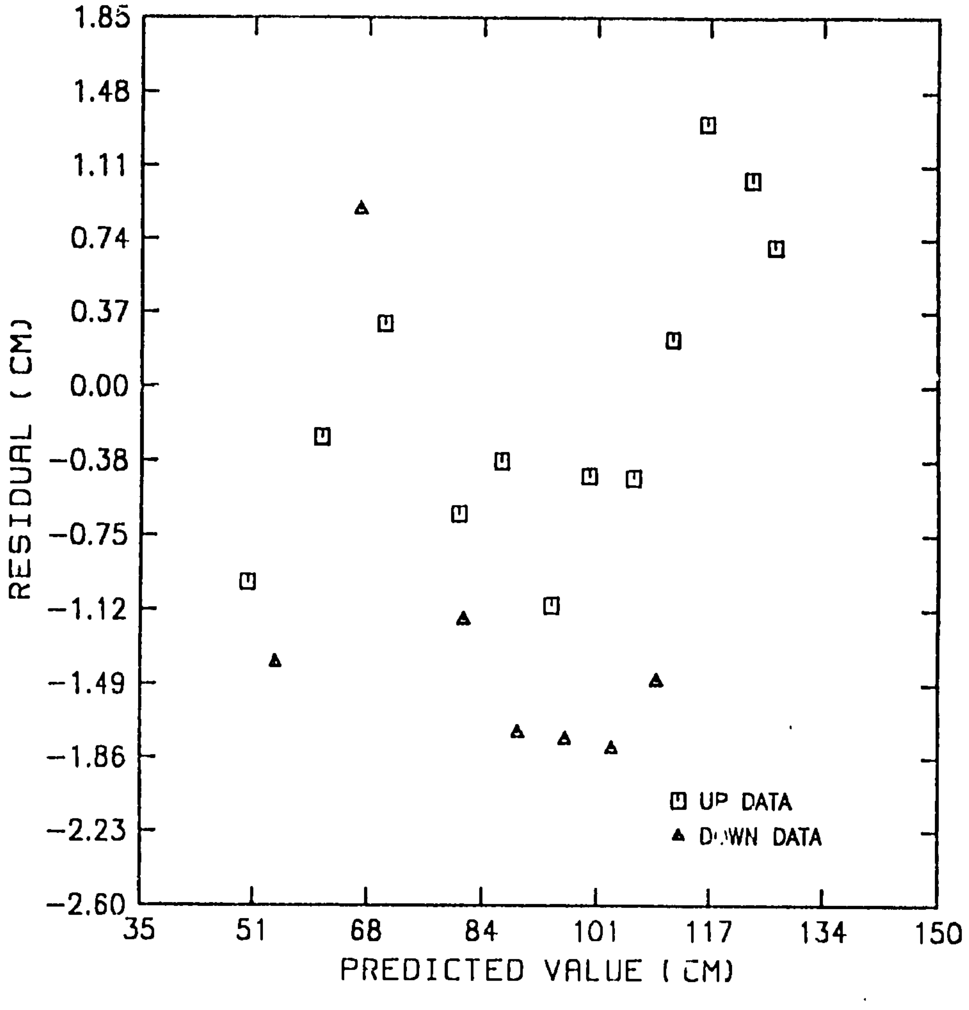

Figure 20. Residual Pattern - Third Pair of Tubes

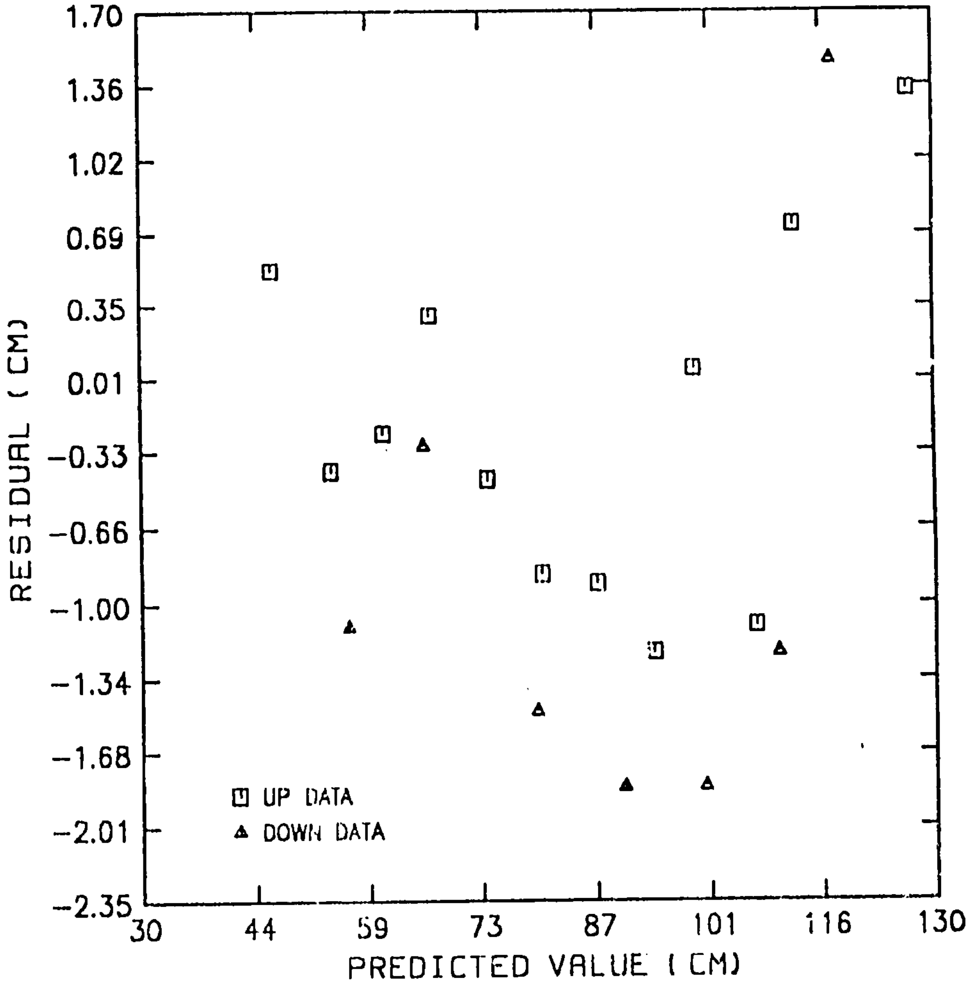

Figure 21. Residual Pattern - Fourth Pair of Tubes

previous combinations of tubes, confirming the established hypothesis (Fig. 22). In order to investigate the significance of the nonuniformities in paint thickness versus irregularities in diameter ratio, the next experiment was carried out with an additional paint coating on the bottom half of inner tube of the sensor. Statistical analysis on the data provided a linear fit with the residual distribution shown in Fig. 23.

- $R^2 = 0.9989$
- Standard error = ± 0.95 *cm*

This indicated a significant difference from the previous pattern with a very prominent break point at the change over point of paint thickness. According to these observations, it could be concluded that, the sensor performance was affected by both the geometrical irregularities and the unevenness of the paint thickness. In order to verify this hypothesis, it was decided to build another capacitor unit according to a different design which is expected to provide better performance characteristics.

To minimize surface irregularities, PVC pipes of diameters 7.5*cm* and 10.2*cm* were used in this trial. The outer surfaces of both pipes were converted to cylindrical conductors by firmly gluing thin Aluminum foil to them. Regular household Aluminum wrapping foil was selected considering its extremely low cost compared to other methods such as electroplating. Electrical connections were made using aluminum wires and screws to minimize electro-chemical reactions and consequent corrosion of the foil. Insulation coating (PITTSBURG Coal Tar Epoxy paint No. 97-640) was manually applied to the foil layer. Two tubes were fixed together as a concentric cylinder capacitor, with the use of two galvanized screws and bolts. Testing was carried out in the same manner as before with the pressure sensor as the reference device. Data for capacitive sensor was automatically collected by the data logger used before (VITRAX Microcontroller).

A simple linear regression according to the model equation [8] provided the following results with the residual pattern shown in Fig. 24.

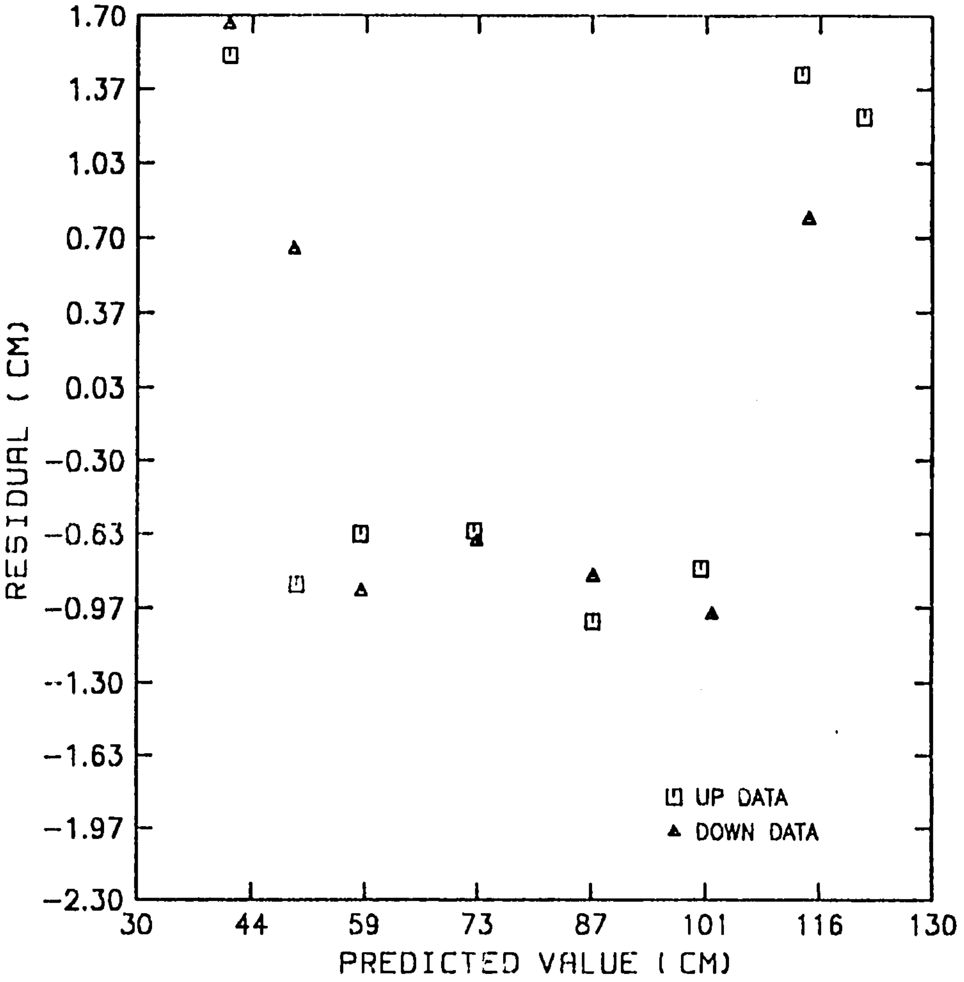

Figure 22. Residual Pattern - Best Combination of Electrodes

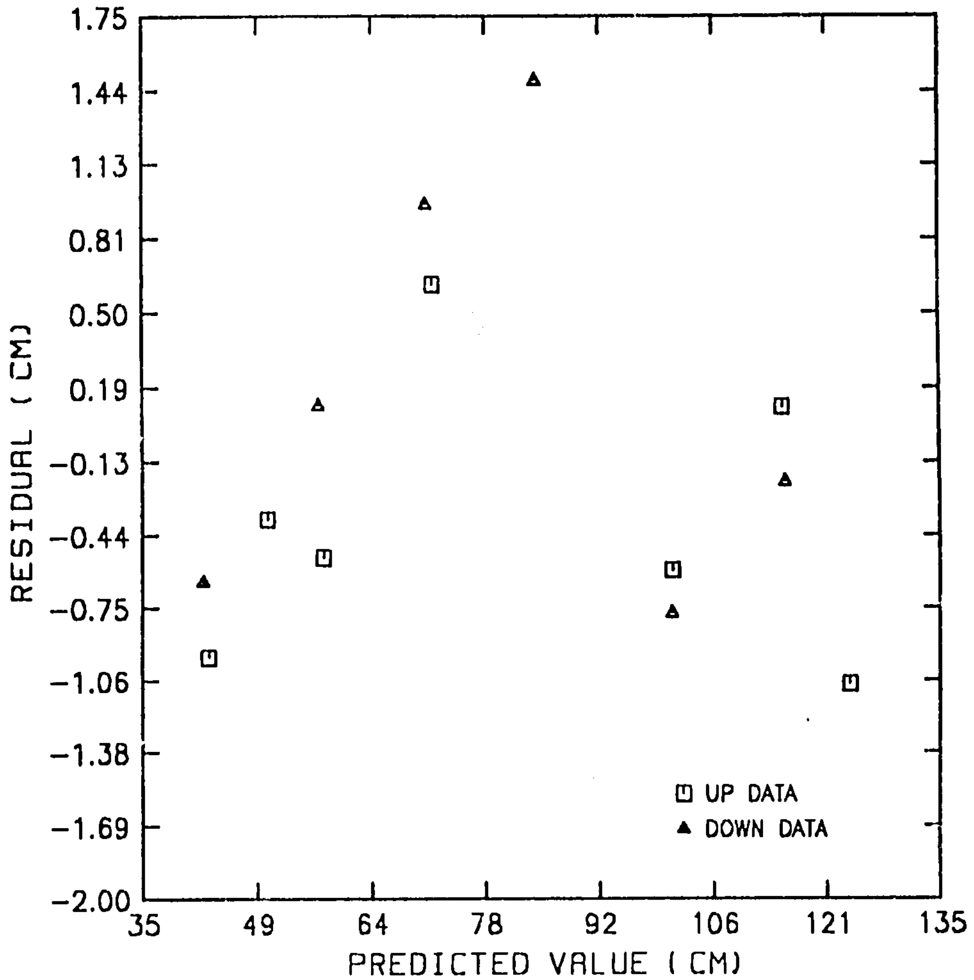

Figure 23. Residual Pattern - Additional Paint Coating on Bottom Half of Inner Tube

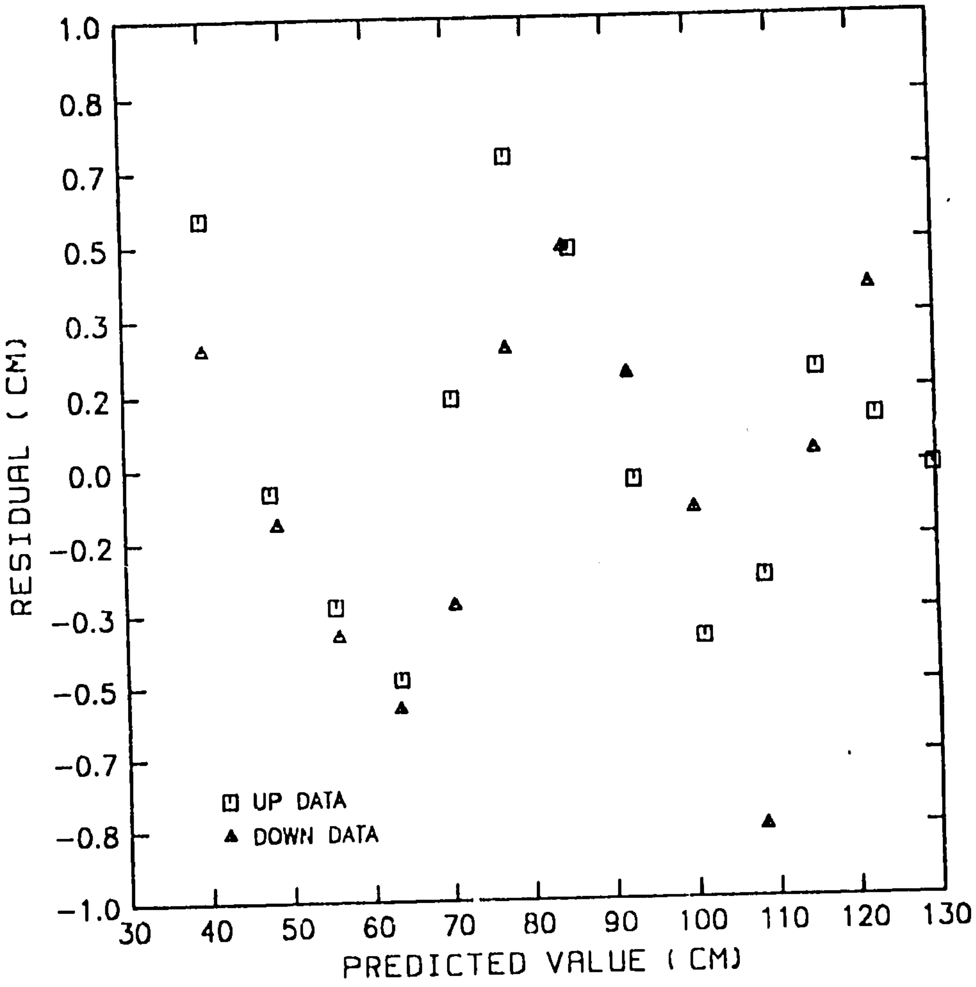

Figure 24. Residual Pattern - Aluminum Coated PVC Pipes

- $R^2 = 0.99$[illegible]

- Standard error = 0.36 *cm*

Performance of the modified sensor was better than the previously developed ones. The same test was carried out again under the same conditions, and analysis of combined data proved that sensor performance was stable over repeated tests (Fig. 25). Please refer to test numbers 1 and 2 in Table 4. Even though there was a pattern in residuals, the error introduced by it was neglected because the overall standard error was sufficiently small. The pattern which still remained was assumed to be due to irregularities in paint thickness. The overall sensitivity was found to be 18 *CCOUNTS* per *cm* and standard error of the prediction by the model was ± 0.44 *cm*. This parameter could be used to calculate the accuracy of the level measurement which was found to be ± 0.87 *cm*.

Major problems encountered in constructing the sensor were gluing the Aluminum foil to the PVC pipe uniformly and painting. Aluminum foil was very easily wrinkled during the process of gluing and provided an irregular surface. Remaining wrinkles were hand pressed firmly using a smooth, hard surface.

Painting was done manually with a regular paint brush. Since the conducting Aluminum layers were attached only to outer surfaces of both PVC pipes, it wasn't necessary to insulate the inside surfaces. The thickness and the surface finish of the PVC pipes were assumed to be sufficiently uniform. Due to the high viscosity of the paint, it was difficult to obtain a perfectly uniform thickness over the whole surface.

The effect of water temperature and salinity on the sensor performance was also examined. First, water was warmed up by keeping in the sun for several hours. Adding hot water directly was not recommended because there was a possibility of changing the chemical properties due to dissolved Chlorine and other chemicals. The temperature (°C) was measured at the beginning, middle, and the end of the experiment. The average was considered as the temperature at which the sensor was tested. Cooling of water was achieved but adding sufficient amount of ice cubes. Again, the average temperature during the test was estimated. These two tests provided similar results with standard errors of ± 0.48 *cm* and ± 0.46 *cm* respectively. Upon examination, it could be seen that the values for the slope (A_2) and intercept (A_1) have changed slightly between experiments. By comparing 95% confidence bands of the regressions, it could be seen that new intercept and slope values of Test 3 are not exactly similar to that of Test 1 or Test 2.

Another test was carried out to investigate the effect of ion concentration in water on the output. In practice, the conductivity in *μMho* is used to represent the salinity of water. As the dissolved salt concentration is increased, the ionized molecules and mobile electrons increase. This lowers the resistance and increases the conductivity. Since the capacitance type sensor employs the water as its dielectric medium, there was a possibility of it being affected by the changes in chemical composition of water. A change in salinity may change the dielectric constant of water and hence the capacitance at a certain water level. On the other hand, it affects the water conductivity, and may thereby change the leakage resistance of the capacitor, and the measured delay time.

To investigate this effect, 25 *g* of salt (Sodium Chloride) was added to the total volume of water used for the experiment after recording the initial conductivity at which the previous experiments were carried out. A digital conductivity meter (Fisher Scientific Corporation) was used to measure the conductivity. This increased the conductivity to 154 *μMho* from its previous value of 124 *μMho*. Consequent tests provided the same linear relationship with R^2 of 0.9992 and standard error of ± 0.47 *cm*. Slight deviations of the intercept and slope values could be noticed. Another 100 *g* of salt was added before repeating the test again giving rise to an increase in conductivity up to 2740 *μMho*. Statistical analysis provided a linear relationship with R^2 of 0.9994 and standard error of ± 0.47 *cm*. A summary of results showing water temperatures and conductivities with the corresponding model parameters is shown in Table 3. In all these tests, the same simple linear model (equation [8]) was used in accordance with the theoretical analysis.

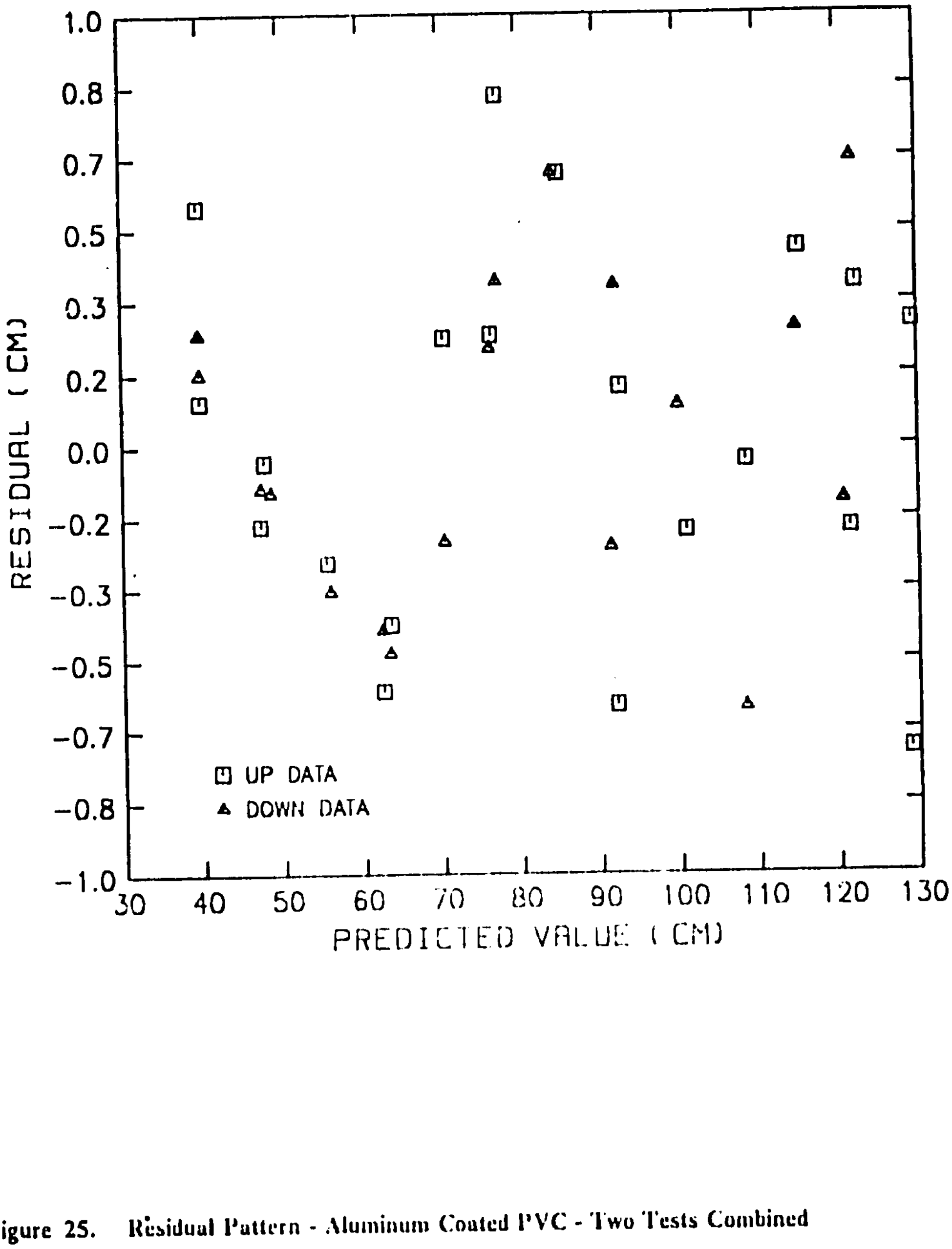

Figure 25. Residual Pattern - Aluminum Coated PVC - Two Tests Combined

By comparing the 95% confidence limits on each of the parameters A_1 and A_2, it was noticed that there was an effect of both temperature and water conductivity on the regression results. In order to test the significance of the effect of temperature and water conductivity, a new model (equation [17]) was used in the regression after combining all the data collected, with temperature (*TEMP*) and water conductivity (*COND*) as another two independent variables in the regression model. F-values obtained for testing the significance of the variables *TEMP* and *COND* were 94.45 and 5.31 respectively. The F-test rejected the null hypothesis that the effects of either *TEMP* and *COND* were insignificant at 95% confidence level. Therefore, it could be concluded that the sensor characteristics were dependant on the temperature and water salinity. However, at a given temperature and conductivity, the measurement accuracy was calculated to be ± 0.87 *cm*.

$$L = A_1 + A_2\,CCOUNT + A_3\,TEMP + A_4\,COND \qquad [17]$$

where:

$A_1 = 54.50$,

$A_2 = 0.0527$,

$A_3 = -0.5385$, and

$A_4 = -0.0425$.

- R^2 obtained = 0.9965

- Standard error = 1.70 *cm*

Table 3. Summary of Results on Capacitive Device

Model:

$L = A_1 + A_2 \, CCOUNT$

Test No.	Water Temp. (° C)	Water Cond. (μMho)	R^2	Std. Error (cm)	A_1 ± Conf.Lim.	A_2 ± Conf.Lim.
1	23.7	124	0.9998	0.39	35.942 ±0.1586	0.0540 ±0.000157
2	23.7	124	0.9998	0.43	35.964 ±0.1337	0.0538 ±0.000133
3	29.4	124	0.9998	0.48	36.222 ±0.2687	0.0489 ±0.000192
4	18.5	124	0.9998	0.46	35.335 ±0.2216	0.0571 ±0.000243
5	23.9	154	0.9992	0.73	36.448 ±0.346	0.0510 ±0.000385
6	25.0	2740	0.9994	0.46	35.818 ±0.3657	0.0517 ±0.000586

Calibration of Potentiometer Sensor

After the potentiometer was properly connected to the weight and float mechanism, (Fig. 11) the unit was installed in one of the pipes of the test stand. Because the relationship between the actual level change in *meters* and the standard pressure sensor output in *volts* had been established, the pressure sensor alone could be used to compare the other devices; capacitance and potentiometer types. Both of the prototypes were activated by the same control circuit after making additional modifications.

The counter output corresponding to potentiometer sensor was denoted by *PCOUNT* and was was directly used in further analysis. Data was statistically analyzed in the same way by taking the pressure sensor as the reference device and converting it to stage in meters (L). The linear model:

$$L = B_1 + B_2 \, PCOUNT \qquad [18]$$

was used in the regression process resulting in:

- $R^2 = 0.999$
- Standard Error = ± 1.08 *cm.*

Upon observation of the residuals, it could be seen that there is a clear margin between residual points for increasing water levels and decreasing water levels (Fig. 26). This was expected and was assumed to be due to the friction in the rotating parts, bearings and other links. The connection between the axle of the potentiometer and the pulley axle was made by force fitting a piece of TYGON tube to both, which made the link more flexible and fairly resistive to torsional moments. This helped to eliminate any undesired bending forces due to slight misalignments. All the bearing points were well lubricated. Consequent tests showed better results with less discrepancy between the two sets of data (Fig. 27).

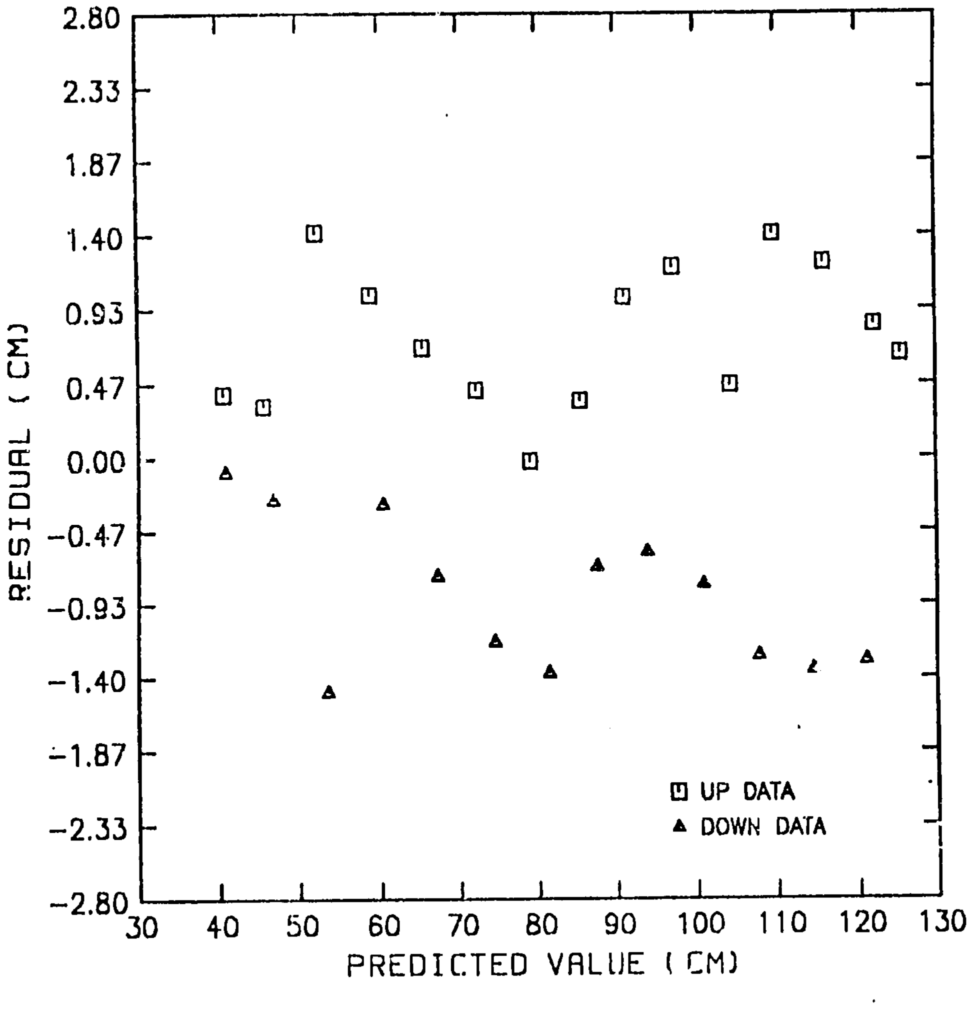

Figure 26. Residual Pattern - Potentiometer Sensor

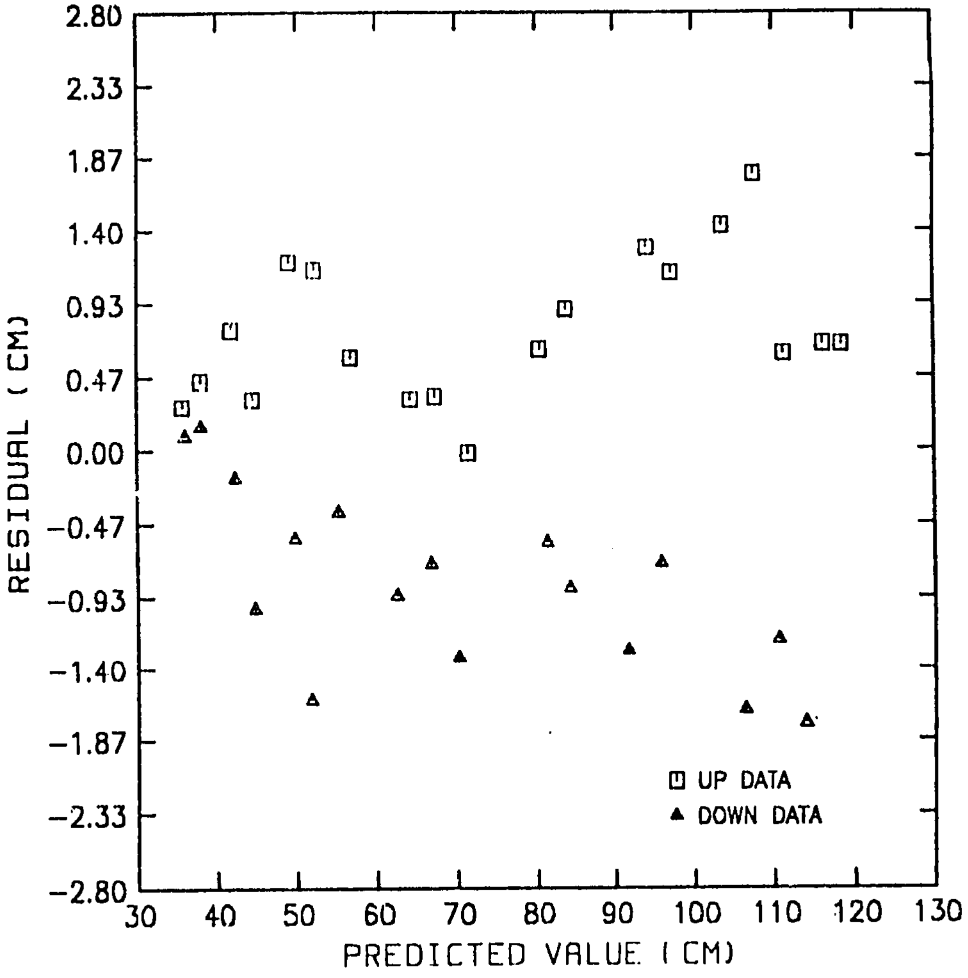

Figure 27. Residual Pattern - After Lubricating the Potentiometer

Upon careful examination, it could still be possible to detect that residual points for up data and down data lie further apart towards the end of the plot which corresponds to higher levels of water, than at the beginning (Fig. 27). Consequent investigations on the experimental setup showed that the cord used to connect the weight and float overwinds when it reaches the sidewall of the pulley when the water level is increased. The additional friction and diameter change has caused the above described error. As a remedy, the axle was properly levelled and cord was placed in such a way that it has sufficient lateral distance to advance along the drum of the pulley for the total range of operation. The Fig. 28 shows subsequent improvements in residual pattern.

The potentiometer device provided stage measurements with a standard error of ± 0.82 *cm*. Therefore, the accuracy of the measurement could be calculated as ± 1.64 *cm* in 1 *m* range. The saw tooth type pattern seen in the final residual distribution (Fig. 28) was caused by the physical setup of the device. Due to practical limitations, the float and weight unit could not be mounted in such a way that the weight moves outside the water container in the test stand (Fig. 13). Therefore, at a certain point, the plunger entered rising water and came out in the same region, when water level was reduced. The length span of the distorted plot being approximately equal to the plunger length (15 *cm*) proved that the error was caused by the above described phenomena. In actual practice, this is avoided by mounting the pulley mechanism at a very high elevation from the maximum water level expected. A summary of model parameters is shown in Table 4.

Analysis of Expenses

Because one of the objectives of this study was to develop a low cost device for water level measurement, a cost analysis was made comparing the expenses of the developed sensors with other available devices (Table 5). Approximate figures for labor costs were used because it was difficult to differentiate between the portion for labor and the other expenses of the project.

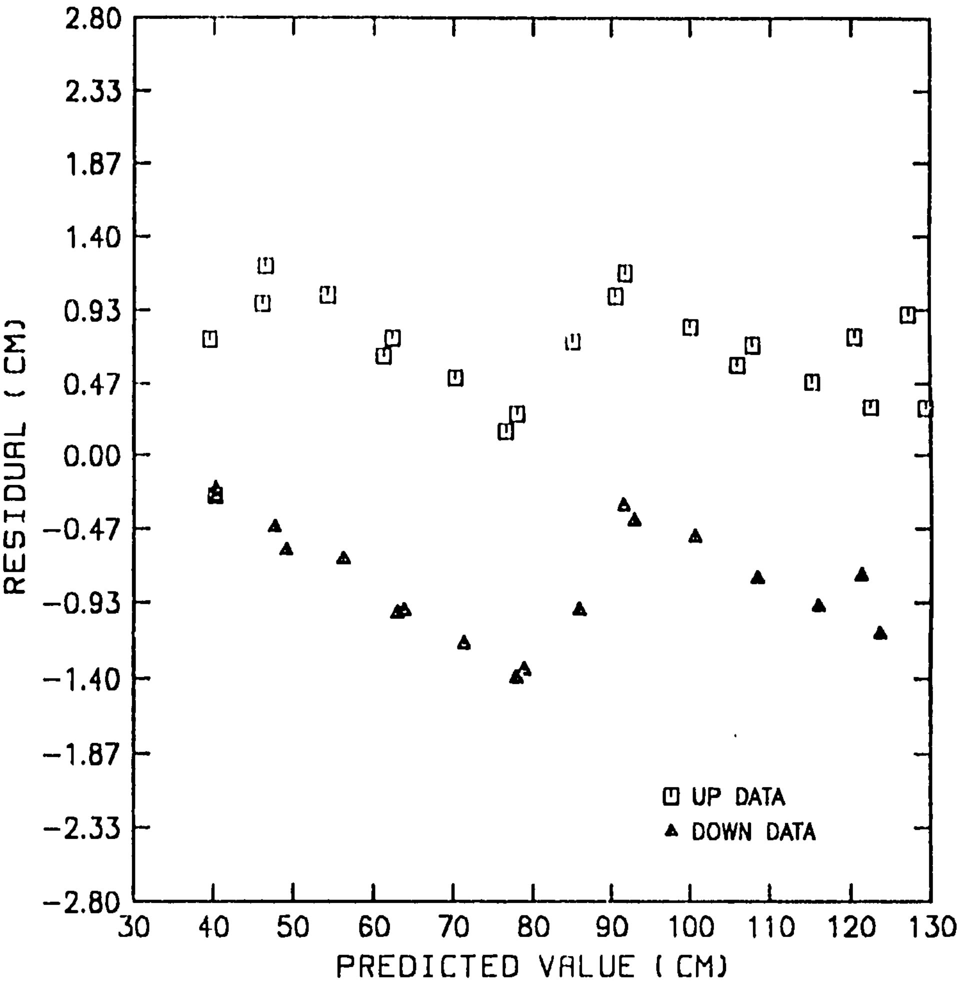

Figure 28. Residual Pattern - Potentiometer - Cord Re-adjusted

Table 4. Summary of Results on Potentiometer Sensor

Model: $L = B_1 + B_2 PCOUNT$			
R^2	Std.Err.(cm)	B_1 ± Conf.Lim.	B_2 ± Conf.Lim.
0.9992	0.82	19.385 ±0.3196	0.0695 ±0.000324

It could be seen from this analysis that the capacitance device is significantly lower in cost. Another advantage was that the materials used (PVC pipes, Aluminum foil, and Paint) were available everywhere in abundance. It was a primary concern that these type of devices would be widely used in less developed countries. The simplicity in construction makes it possible to manufacture this type of sensor in such countries, without any sophisticated technology, further lowering the labor cost. The following is an itemized description of each task and related expenses.

Capacitance Type Sensor

Task:	Construct the sensor from PVC pipes, Aluminum foil and coat with insulating paint, attach electrical connectors.
Material cost:	U.S.$ 16.10
Type of Labor:	Low skill
Estimated time:	1.5 Hrs. per unit.
Estimated labor cost:	U.S.$ 9.00

Potentiometer Sensor.

Task:	Machine pulley, mounting bracket, and assemble
Material cost:	U.S.$ 120.00
Type of labor:	Medium skill (machining)
Estimated time:	5.0 Hrs. per unit.
Estimated labor cost:	U.S.$ 50.00

Data Logger

Task: Assemble hardware circuits, test, program the EPROM controller.

Material cost: U.S.$ 141.00

Type of Labor: Medium skill

Estimated time: 3.0 Hrs. per unit.

Estimated labor cost: U.S.$ 30.00

Calibration of Sensors

Task: Test for proper operation, carry out a calibration test, compute the conversion factors, percentage errors.

Type of labor: High skill

Estimated time: 4.0 Hrs.

Estimated labor cost: U.S.$60.00

The following is a summary of other operations related to maintenance and retrieval of data from sensors. All systems (2 - 8) listed in Table 5 require these services for proper maintenance. An average time for each task is presented here on per-year basis. An approximate figure for annual cost was calculated for each system by considering the value of equipment and maintenance cost over a period of 5 Years.

Field Calibration

Type of labor	High skill
Frequency	Semiannual
Time per Year	10 Hrs.
Cost	U.S.$ 225.00

Data Retrieval

Type of labor	Low skill
Frequency	Weekly
Time per Year	30 Hrs.
Cost	U.S.$ 150.00

Data Reduction/Error Detection

Type of labor	Medium skill
Frequency	Weekly

Time and Cost per Year

Electronic recording - 20 Hrs. (U.S.$ 200.00)

Chart type - Electronically - 45 Hrs. (U.S.$ 450.00)

Chart type - Manually - 60 Hrs. (U.S.$ 600.00)

Cleaning

Type of labor	Low skill
Frequency	Weekly[3]
Time per Year	12 Hrs.
Cost	U.S.$ 60.00

Power

Task	Replacement of batteries
Frequency	Monthly
Cost per Year	U.S.$ 60.00

A major portion of the estimated annual cost consisted of expenses for labor for manufacturing and maintenance. Because U.S. labor costs were used in estimating these figures, the effect of using a low cost device made less of a difference in the final annual cost. Labor costs would be drastically reduced if these devices were installed and maintained in a less developed country where manual labor is cheaper than in the U.S. Another advantage of the developed capacitive sensor was its simple design, and the possibility of it being manufactured in less developed countries, further reducing the final cost of equipment. By taking these facts into consideration it could be said that the developed sensor would be more competitive when used in less developed countries.

---

[3] Highly site-specific. Equal time is assumed for all sensors

Table 5. Summary of Analysis of Expenses

System	Component Name	Value (US$)
1. Data logger	VITRAX-IX Microcontroller	140.00
	Other components	1.00
	Mounting bracket and enclosure	50.00
	Labor cost	30.00
	Total	220.00
2. Capacitive sensor	2 *m* PVC pipes	10.35
	Screws and nuts	1.00
	2 *m* Aluminum wrapping foil	0.50
	Spray adhesive, Insulating paint	4.25
	Labor cost	9.00
	Sub total	25.10
	Data logger (above)	220.00
	Data retrieval (Tandy 1400LT)	1500.00
	Maintenance (5 years)	3475.00
	Approximate annual cost	1044.00
3. Potentiometer sensor	Variable resistor	40.00
	Pulley, Float, Weight, Cable and fixtures	80.00
	Labor cost	50.00
	Sub total	170.00
	Data logger (above)	220.00
	Data retrieval (Tandy 1400LT)	1500.00
	Maintenance (5 years)	3475.00
	Approximate annual cost	1073.00
Other available systems	4. Sierra-Misco Model 5050LL-PTF	770.00
	Data logger (Campbell CR10)	1205.00
	Data retrieval (Tandy 1400LT)	1500.00
	Maintenance (5 years)	3475.00
	Approximate annual cost	1390.00
	5. Float and Weight type digital punch tape recorder	2275.00
	Digital punch tape reader	5000.00
	Maintenance (5 years)	2500.00
	Approximate annual cost	1955.00
	6. Bubbler type transducer	7620.00
	Data logger (Campbell CR10)	1205.00
	Data retrieval (Tandy 1400LT)	1500.00
	Maintenance (5 years)	3475.00
	Approximate annual cost	2760.00
	7. Sonar device	1230.00
	Data logger (Campbell CR10)	1205.00
	Data retrieval (Tandy 1400LT)	1500.00
	Maintenance (5 years)	3550.00
	Approximate annual cost	1497.00
	8. Float and Weight type chart recorder	1097.00
	Maintenance (5 years)	4800.00
	Approximate annual cost	1430.00
	9. Point gage (manual operation)	538.00

Conclusions and Recommendations

Based on the results of the experiments and related analysis, the following conclusions were made:

1. The capacitive type water level sensor could be used to measure water level with an accuracy of ± 0.87 *cm*. When a 1 *m* operating range is considered, the percentage accuracy could be expressed as 0.87% of the operating range.

2. The resistance pot type sensor also provided stage data with an accuracy of ± 1.64 *cm*. That could be interpreted as 1.6% accuracy of the transducer range of 1 *m*.

3. The capacitance sensor had the advantage of being inexpensive compared to other devices. As it was found that sensor performance was affected by some environmental factors such as water temperature and salinity, remedial modifications were suggested for future developments.

4. Resistance pot type sensor could be directly employed to improve conventional float and weight type chart recorders by converting data to digital format directly.

5. The sensing technique developed (capacitance charging principle) provided accurate data with the use of minimal hardware.

6. The data logging system was capable in actuating the sensors, measuring time delay, computing the average, and storing collected data along with the time, date, and year. It also facilitated down loading of data to another permanent storage device. This made it possible to service remote installations and collect data on a routine basis.

Recommendations for Further Improvements

Even though the capacitive sensor was capable of providing stage data accurately, it was found that its performance is affected by the water temperature and salinity to a certain extent. The combined model, equation [17], provided a standard error of ± 1.70 *cm* for any temperature and water conductivity value in the range tested. Therefore, the device could still be used in any environment with a lesser degree of accuracy. The following recommendation is made as a possible improvement to the system when a higher accuracy is required over a wide range of operating environments.

Reference Capacitor

If a reference capacitor of smaller length but same diameter ratios is added to the system, it could be used to estimate the changes in parameters which affect the time delay. This reference unit must be installed so that it is totally submerged in water during all periods of operation. Since it is fully submerged, the time delay imposed by the reference capacitor will be only dependant on factors such as dielectric constant, water conductivity, and temperature. In the event that any of these factors changes, the time delay imposed by both reference and sensing capacitors will change in the same manner. Therefore, the time delay ratio between the two capacitors would provide a true figure of the water level change, eliminating the effect of other parameters.

The necessary hardware and software changes must be made so that the data logger activates both the sensing capacitor and the reference capacitor and computes the ratio of time delays measured. This sequence of operations could be repeated several times to achieve increased accuracy.

Electroplating

Another method of manufacturing cylindrical electrodes for capacitive sensors has been investigated. It has been found that there are molding processes to manufacture two pipes as a unit and electroplate each surface with a conductive material. This method has the advantages of being able to provide much more uniform and smooth surfaces and is free from errors due to loose mounting flanges. Approximate cost for manufacturing such a unit was found to be U.S.$88.94 per tube (for a total of 5) and U.S.$30.00 per tube (for a total of 25) including a conductive coating. This method is especially recommended for large scale production which would be more economical when compared to the labor costs of the other manual construction. Further investigations are required to establish the effect of the surface resistance of the conductive coating if any.

Summary

The following ideas are listed as a summary of recommendations to improve the system performance:

1. Even though sufficiently comprehensive laboratory tests were carried out, the units could not be tested under actual field conditions. Therefore, it is recommended that a field test is carried out before installing the system for actual use.

2. It is also suggested that a new system be developed incorporating a reference capacitor to achieve better accuracies in a wide range of field conditions.

3. The performance of resistance pot type sensor could be improved by using a sprocket - chain drive in place of the conventional pulley and cord. This eliminates errors due to over winding and minimizes frictional resistance effects.

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Appendix A. BASIC Program

```
100 OUT 195,154
200 DIM E(100,12)
300 R = 0: Z = 0
400 PRI " INPUT COMMAND (0-ACTIVATE, OTHER-DUMP DATA)": INPUT T
500 IF T > 0 THEN GOTO 660
510 R = R + 1
520 FOR I = 1 TO 11
525 IF Z = 1 THEN GOTO 535
530 OUT 194,11: OUT 194,2: GOTO 540
535 OUT 194,11: OUT 194,1
540 A = INP(194): B = INT(A/16)
550 IF B > < 0 THEN GOTO 540
560 C = INP(192): D = INP(193)
570 OUT 194,3
580 E(R,I) = C + (256 * D)
585 FOR W = 1 TO 750: NEXT W
590 NEXT I
600 Y = 0: FOR H = 2 TO 11: Y = Y + E(R,H). NEXT H
602 Y = Y/10
603 T = 0
604 FOR H = 2 TO 11
605 T = T + ( E(R,H) - Y) * ( E(R,H) - Y): NEXT H
606 S = 100 * ( SQR(T/9))/Y
607 PRI " STANDARD DEVIATION = ";S
608 IF S > = 1.2 THEN GOTO 850
610 PRI " ERRORS WITHIN LIMITS - PROCEED TO NEXT STEP "
612 IF Z = 0 THEN Z = 2
613 IF Z = 1 THEN Z = 0
620 E(R,12) = Y
625 IF Z = 2 THEN Z = 1: PRI " POT EXCITATION BEGINS... ": GOTO 510
640 GOTO 400
660 PRI "*"
680 FOR L = 1 TO R: FOR M = 1 TO 12: PRI E(L,M);
700 NEXT M: PRI " "
720 NEXT L
800 STOP
850 PRI " ERRORS TOO LARGE BOY - TRYING AGAIN "
855 GOTO 510
```

Appendix B. Modula-2 Program

```
MODULE WLLOG2;
FROM SBBIO1 IMPORT IOGet, IOPut, Sleep;
(* IOPut(Port,Value) *)
(* This is VER 1.2 of WLLOG - Water level logger.    *)
(* Error checking with Std. deviation is implemented *)
(* in this version                                   *)
FROM RKBTERM IMPORT Write,WriteLn,WriteString,WriteCard;
FROM SYSTEM IMPORT BYTE;

CONST maxstorage = 15000;
VAR M10SEC[8000H],  (* 0.01 second counter, not implemented      *)
   M1SEC[8001H],   (* 0.1 second counter, count done in assembly *)
   MSEC[8002H],    (*   second counter *)
   MMIN[8003H],    (*   minute counter *)
   MHR[8004H],     (*   hour counter   *)
   MLDAY[8005H],   (*   low byte of day counter  *)
   MHDAY[8006H] : BYTE; (* high byte of day counter *)
         (* NOTE years not implemented in assembly lang.   *)
   mc[8007H]   : CHAR; (* character from serial 1 interrupt    *)
   od          : BOOLEAN;
   seconds,   (* the current seconds from the clock *)
   osec,
   mints,     (* the current minutes from the clock *)
   hours,     (* the current hours from the clock   *)
   days,      (* the current days from the clock    *)
   year,      (* the current year from the clock    *)
   count,
   Lsec,      (* the seconds the last time through check clock  *)
   Lmints,    (* the minutes the last time through the software *)
   Lhours,    (* the hours the last time through the software   *)
   ctimeset,  (* ctime at which the clock is changed             *)
   ctime,     (* for correcting the clock                       *)
   check,     (* check for repetitions within a single minute   *)
   G,         (* code for activating CAP and POT                *)
   N,         (* minutes segment                                *)
   trial,     (* trial number - to limit to 3 in case of error  *)
   spcount,   (* intermediate count - proc storecnt             *)
   I1         : CARDINAL; (* code to sense charging time        *)
   data       : ARRAY[1..maxstorage] OF CARDINAL;
              (* for storing the logged data and time           *)
   inpbuf     : ARRAY[1..30] OF CHAR;
```

```
            (* for storing the data from the serial port      *)
  E          : ARRAY[1..11] OF CARDINAL; (* temp storage        *)
  stptr,     (* pointer to the next place in storage to use    *)
  otptr,     (* pointer to the next place in storage to output *)
  inpbuf_ptr  : CARDINAL;  (* pointer into inpbuf *)
  resp       : CHAR;
  stderr     : CARDINAL; (* standard error within 10 datapts       *)

PROCEDURE ReadCard():CARDINAL;
VAR  i    :CARDINAL;
   ch   : CHAR;
   done : BOOLEAN;

PROCEDURE strip(val:CHAR):CHAR;
VAR ich  : CARDINAL;
BEGIN
ich := ORD(val);
IF ich  >  128 THEN val :=  CHR(ich-128) END;
RETURN(val);
END strip;

BEGIN
done := FALSE;
REPEAT
  REPEAT UNTIL mc< >CHR(0);
  ch := mc; mc := CHR(0);
  ch := strip(ch);
  Write(ch);
UNTIL NOT((ch>'9')OR(ch<'0'));
i := ORD(ch)-48;
REPEAT
  REPEAT UNTIL mc< >CHR(0);
  ch := mc; mc := CHR(0);
  ch := strip(ch);
  Write(ch);
  IF (ch<'0')OR(ch>'9') THEN done :=  TRUE END;
  IF (i>6553)OR((ORD(ch)>54)AND(i=6553)) THEN done :=  TRUE END;
  IF NOT done THEN i := i*10+ORD(ch)-48 END
UNTIL done;
RETURN(i);
END ReadCard;

PROCEDURE ReadCh():CHAR;
VAR ch    : CHAR;
BEGIN
REPEAT UNTIL mc< >CHR(0);
ch := mc; mc := CHR(0);
Write(ch);
RETURN(ch)
END ReadCh;

PROCEDURE store(datapt:CARDINAL);
BEGIN
WriteString('st. proc. ent. ');
WriteCard(datapt);
WriteString(' was stored at ');
```

```
 WriteCard(stptr);
 WriteLn;
 data[stptr] := datapt;
 INC(stptr);
 IF stptr >maxstorage THEN stptr := 1; END;
 END store;

 PROCEDURE sthours;
 BEGIN
 store(32000+year);
 store(days*32+hours);
 END sthours;

 PROCEDURE check_cl;
 VAR cs,cm,ch,cd : CARDINAL;
    (* for checking that the clock has not changed during fetch of time *)
 BEGIN
 REPEAT
   seconds := MSEC; mints := MMIN; hours := MHR; days := 256*MHDAY+MLDAY;
   cs      := MSEC; cm    := MMIN;   ch := MHR; cd   := 256*MHDAY+MLDAY;
 UNTIL (seconds=cs) AND (mints=cm) AND (hours=ch) AND (days=cd);
 IF hours < > Lhours THEN sthours; Lhours := hours  END;
 IF mints < > Lmints THEN Lmints := mints  END;
 IF seconds < > Lsec THEN Lsec := seconds; INC(ctime) END;
 IF ctime> ctimeset THEN
    ctime := 01; REPEAT UNTIL MISEC < 8; MISEC:=MISEC+1 END;
    (* will add one tenth second every ctimeset seconds *)
 IF days > 365 THEN
    IF (year = 1992) OR
       (year = 1996) OR
       (year = 2004) THEN
        IF days > 366 THEN days := 1; INC(year) END;
    ELSE days := 1; INC(year) END
 END;
 END check_cl;

 PROCEDURE pause; (* impose a delay in between samples  *)
  VAR wait : CARDINAL;
   BEGIN
   wait := 1;
   REPEAT
   wait := wait + 1
  UNTIL wait = 10000; (* change this to control delay time *)
 END pause;

 PROCEDURE errcheck; (* to calculate stderr *)
  VAR total, I : CARDINAL;
   BEGIN
    total := 0;
    FOR I := 2 TO 11 DO
    total := total + ( E[I] - count )*( E[I] - count );
    END;
   stderr := total DIV 9 + total MOD 9;
   stderr := 100 * (stderr DIV count + stderr MOD count);
 END errcheck;
```

```
PROCEDURE excite; (* excitation of sensors *)
 VAR A,B,C,D,T,I, : CARDINAL;
  BEGIN
   IOPut (0C3H,09AH); (* to configure PIA ports as reqd *)
   FOR I := 1 TO 11 DO
    IOPut (00CH,0FFH); IOPut (00DH,0FFH); (* load PRT-CH0 with FFFFH *)
    IOPut (010H,023H); IOPut (0C2H, (G)); (* decrement PRT, activate CAP or POT *)
     REPEAT
     A := IOGet (0C2H) DIV (H) (* H = 50 for CAP, = 49 for POT *)
     UNTIL A < 1;
    IOPut (010H,022H); (* stop PRT-CH0 *)
    C := IOGet (00CH); D := IOGet (00DH); (* read TMDR-CH0: low byte, high byte *)
    IOPut (0C2H,003H); (* de activate CAP or POT *)
    E[I] := 65535 - (C + (256 * D)); (* number of counts *)
   pause (* delay between samples *)
   END;
  T := 0;
  FOR I := 2 TO 11 DO
  T := T + E[I] (* sub total of ten samples *)
  END;
  count := (T + 5) DIV 10; (* average of 10 readings *)
  errcheck;
 END excite;

 PROCEDURE storecnt;
  BEGIN
   REPEAT
    trial := trial + 1;
     excite;
     spcount := spcount + count;
     IF stderr < 4 THEN trial := 3 END;
   UNTIL trial = 3;
   IF stderr > = 4 THEN count := (((spcount * 2) + 3) DIV 6); END;
  IF count > 7424 THEN store(N * 4096)
   ELSE store(N * 4096 + count)
  END;
 trial := 0; spcount := 0;
 END storecnt;

  PROCEDURE getdata;
  BEGIN
   N := mints DIV 10; (* sample number within the hour          *)
   spcount := 0;
   trial := 0;
    IF N < > check THEN (* wouldn't repeat twice in one minute *)
     IF ((mints DIV 10 + mints MOD 10) - N ) = 0 THEN (* every 10 minutes        *)
     G := 02H; H := 50; storecnt; (* excitation of CAP          *)
     G := 01H; H := 49; storecnt; (* excitation of POT          *)
     check := N;          (* remember prev mints segment        *)
     END
    END
  END getdata;

  PROCEDURE command;
  VAR i, j : CARDINAL;
     cmnd : CHAR;
```

```
 vl   : CARDINAL;
  otpt_year,
  otpt_day,
  otpt_hour,
  otpt_min,
  otpt_count  : CARDINAL;

PROCEDURE otpt(VAR ptr:CARDINAL);
BEGIN
IF data[ptr] > 32000 THEN otpt_year :=  data[ptr]-32000;
  INC(ptr);
  otpt_day    :=  data[ptr] DIV 32;
  otpt_hour   :=  data[ptr] MOD 32
 ELSE otpt_min  :=  data[ptr] DIV 4096;
    otpt_count :=  data[ptr] MOD 4096;
    WriteString('990,');
    WriteCard(otpt_year MOD 100);
    WriteString(',');WriteCard(otpt_day);
    WriteString(',');WriteCard(otpt_hour*100 + otpt_min);
    WriteString(',');WriteCard(otpt_count);
    WriteLn
 END END otpt;

 PROCEDURE showat;
 BEGIN
 WriteString('storage ptr = '); WriteCard(stptr);
 WriteString(' output ptr = '); WriteCard(otptr); WriteLn;
 END showat;

 PROCEDURE docommand;
 VAR k   : CARDINAL;
 BEGIN
 CASE cmnd OF
 (* A - print the pointers
   nB - set the output pointer back n (if n is blank n  =  -1)
   nC - if n is blank show the clock
        if n is present set the minutes to n, and the seconds to 0
   nD - display n data points, if n is blank n = 1
   nG - set the output pointer to n, n must not be 0
   nS - show the number stored an the n locations, if n is blank n = 1
 *)
 'A' :   showat |
 'B' :
     IF vl = 0 THEN vl: = 1 END;
     IF otptr  >  vl THEN otptr :=  otptr-vl ELSE otptr :=  1 END;
     showat |
  'C' :
     IF vl  > 0 THEN MISEC :=  0; MSEC :=  0; MMIN :=  vl-1      END;
     WriteString('year  = '); WriteCard(year); WriteLn;
     WriteString('date  = '); WriteCard(days); WriteLn;
     WriteString('time  = '); WriteCard(hours); WriteString(':');
     WriteCard(mints); WriteString(':');
     WriteCard(seconds); WriteLn;
     WriteLn |
  'D' :
     IF vl = 0 THEN vl: = 1 END;
```

```
  IF otptr  < 2 THEN otptr :=  2 END;
  WHILE (data[otptr] < 32000) AND (otptr > 0) DO DEC(otptr);
     END;
  LOOP
     IF otptr < stptr THEN otpt(otptr) ELSE EXIT END;
     IF vl = 0 THEN EXIT END;
     IF mc < > CHR(0) THEN EXIT END;
     INC(otptr); DEC(vl)
   END;
   showat |
'G' :
   otptr :=  vl;
   IF otptr  >  maxstorage THEN otptr :=  maxstorage; END;
   IF otptr  <  1 THEN otptr :=  1 END;
   showat |
'S' :
   IF vl  = 0 THEN vl :=  1 END;
   IF vl > 20 THEN vl :=  20 END;
   FOR k :=  1 TO vl DO
      WriteCard(data[k]); WriteLn; END;
   showat |
 ELSE WriteString('BAD command *')
 END (*CASE*);
 WriteLn END docommand;

 BEGIN
  WriteLn;
  FOR i :=  1 TO inpbuf_ptr DO
    IF ORD(inpbuf[i]) > 127 THEN inpbuf[i] :=  CHAR(ORD(inpbuf[i])-128); END END
  i :=  1;
  WHILE (inpbuf[i] < 'A') DO INC(i) END;
  cmnd :=  inpbuf[i];
  vl :=  0;
  FOR j :=  1 TO i-1 DO vl :=  vl*10 + ORD(inpbuf[j])-48 END;
  WriteString('commad  = '); Write(cmnd); WriteString(' vl  = ');
  WriteCard(vl);
  WriteLn;
  docommand;
  inpbuf_ptr :=  0
 END command;

 PROCEDURE check_inp;
 VAR ch : CHAR
 BEGIN
 (* IOPut(01H,070H),  Clear all errors and error interrupts *)
 ch :=  mc; mc: = CHR(0);
 IF ch  =  CHR(8) THEN DEC(inpbuf_ptr); Write(ch)
 ELSE
   INC(inpbuf_ptr); inpbuf[inpbuf_ptr] :=  ch;
   Write(ch);
   IF ch  =  CHR(13; THEN command END
  END
  END check_inp;

  BEGIN
  mc :=  CHR(0);
```

```
L.mints := 0;
L.hours := 0;
inpbuf_ptr := 0;
IOPut(003H,06H)    (* set baud, CNTLB1 port = 003H, second # -> baud rate *)
                   (* baud rate: 06 = 600 baud            *)
IOPut(001H,074H)   (* turn on serial port 1   *)
IOPut(005H,008H)   (* turn on ser 1 interrupt *)
WriteLn;
WriteString(' ***********************************'); WriteLn;
WriteString(' * WATER LEVEL LOGGER - VERSION 1.2 *'); WriteLn;
WriteString(' ***********************************'); WriteLn;
WriteLn;
WriteString('   Do you want to set clock');WriteLn;
WriteString('   and zero pointers?');WriteLn;
WriteString('   (This will erase any data.)');WriteLn;
REPEAT UNTIL mc <> CHR(0);
resp := mc; mc := CHR(0);
IF (resp = 'Y') OR (resp = 'y') THEN
  WriteLn;
  stptr := 1;
  otptr := 1;
  WriteLn;
  WriteString(' Enter the Year (1989)  ');
  year := ReadCard();
  WriteLn;
  WriteString(' Enter the date - day of year only  ');
  days := ReadCard();
  MHDAY := days DIV 256;
  MLDAY := days MOD 256;
  WriteLn;
  WriteString(' Enter the time - hours only  ');
  hours := ReadCard(); MHR := hours;
  WriteLn;
  WriteString('  seconds will be set to 0'); WriteLn;
  WriteString('  when minutes are entered'); WriteLn;
  WriteString('  Enter the time - minutes only ');
  mints := ReadCard(); MISEC := 0; MSEC := 0; MMIN := mints;
  WriteLn;WriteString(' '); WriteCard(mints);
  WriteString(' was entered'); WriteLn;
  WriteString('Enter the clock correction factor (820) ');WriteLn;
  ctimeset := ReadCard();WriteLn;
  ctime := 0;
  osec := 0;
  count := 0;
  od := FALSE;
  check := 99;
END;
LOOP
  Sleep;
  IF mc <> CHR(0) THEN check_inp      (* interrupt was from ser. port *)
    ELSE check_cl; getdata;          (* interrupt was from timer     *)
    END
  END
END WLLOG2.
```

Appendix C. AHPL Program and Output

Program

```
AHPLMODULE: SENSOR.
 EXINPUTS: R.
 OUTPUTS: LOAD;CLEAR;CLKIN.

1 LOAD = R;
 CLEAR =\0\;
 = >(¬R)/(1).
2 CLEAR = R;
 LOAD =\0\;
 = >(R,¬R)/(2,1).
ENDSEQUENCE
CONTROLRESET(1);
CLKIN = ¬R.
END.
```

Output Listing

```
    1        AHPLMODULE: SENSOR.
    2         EXINPUTS: R.
    3         OUTPUTS: LOAD;CLEAR;CLKIN.
    4
    5        1 LOAD = R;
    6         CLEAR =\0\;
    7          = >(¬R)/(1).
    8        2 CLEAR = R;
    9         LOAD =\0\;
   10          = >(R,¬R)/(2,1).
   11        ENDSEQUENCE
   12        CONTROLRESET(1);
   13        CLKIN = ¬R.
   14        END.
   15
HIPSIM COMMUNICATION SECTION FOR THE ABOVE MODULES
DATE: 07/17/89   TIME: 15:04:39

   16        CLOCKLIMIT 15.
   17        EXLINES
```

```
18        R = 1,1,0,0,0,0,0,1,1,1,1,0,0,0,0.
19        OUTPUTS R;LOAD;CLEAR;CLKIN.
20        DUMP ALL.
21
22

 :::: EXECUTION WILL STOP AFTER   15 CLOCK PULSES ::::
IAHPL FUNCTION LEVEL SIMULATOR OUTPUT IS LISTED BELOW :

            R
LOAD
                    CLEAR
                     CLKIN
    CLOCK #
       1  1 1 0 0
       2  1 0 1 0
       3  0 0 0 1
       4  0 0 0 1
       5  0 0 0 1
       6  0 0 0 1
       7  0 0 0 1
       8  1 1 0 0
       9  1 0 1 0
      10  1 0 1 0
      11  1 0 1 0
      12  0 0 0 1
      13  0 0 0 1
      14  0 0 0 1
      15  0 0 0 1

 :::: PROGRAM REACHED THE CLOCKLIMIT. INTERPRETER STOPS ::::
```

Vita

The author, Pulathisi Mahinda Kumara Alahakoon was born in Kegalle, Sri Lanka in April, 1962. After completing his high school education in Kegalu Maha Vidyalaya, he entered the University of Peradeniya for his B.Sc. degree in Electrical and Electronic Engineering. After graduation in December, 1984, he joined the department of Electrical and Electronic Engineering as an Assistant Lecturer. He got married in 1986 to Aruni, whom he met in his high school life.

As he was interested in application oriented research and higher studies, he started working on a Master of Science degree in Agricultural Engineering at Virginia Polytechnic Institute and State University in the field of Electronic Applications in Agriculture.

Upon completion of the MS degree, he plans to continue for a Ph.D. and return to his home country to resume duties in a university academic staff position.

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PRESENTATION

A LOW COST HYDROLOGIC DATA LOGGER

by

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SUMMARY: A microprocessor based data logger was developed to control and collect data from two types of water level sensors. A capacitance probe and a resistance pot type sensor were constructed and calibrated against a pressure sensor. It measured stage with an accuracy of ± 1.213 cm.

KEYWORDS:
Irrigation, Stage, Instrument, Sensors, Logging

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114

A Low Cost Hydrologic Data Logger

P. M. K. Alahakoon, R. K. Byler, S. Mostaghimi, P. W. McClellan

Introduction

Agricultural development is one of the most important factors to the economic development of the large number of less developed countries. Major investments have been made by many governments in irrigation system development as the primary step to increase agricultural productivity. But, frequently such irrigation development works have failed to produce the intended improvements in agricultural productivity due to poor management of irrigation water. Wicham and Valera (1978) mention that: 'While it is generally agreed that better water management is needed, it is not clear what is required to achieve it. What do we really mean by improved water management, how it can be attained ?'

There are some manual devices for measuring and regulating water flow through canals such as weirs, flumes, and division boxes which are presently in use. There are two means by which the discharge into any distributory offtake can be controlled. The first is the regulation of the water elevation at the distributory canal. The second is the control of gate settings at the outlet openings. But in the absence of the former, which requires proper measurement of water level, the latter becomes totally ineffective. Even though very sophisticated devices have been built for the purpose of sensing and recording water level in such systems, the expense has restrained them from being widely used.

The project objective is to design and build a Sensor - Data Logger unit for the improvement of water management facilities. In particular, the problem of sensing the water level in canal type irrigation systems and recording of digital data for the purpose of continuous monitoring will be dealt with in this study.

Historical Background

The earliest type of level measurement can be classified as using point contact devices. In its most primitive form, a notched stick was used which provided a rough measurement of height of water above an arbitrary reference point. Man's perpetual effort to make his activities more refined and accurate, led to the design of the hook gage, point gage, and steel tape and plumb-bob gage, which make use of the same principle of measuring the distance to the top surface of reservoir from a datum. Norton (1969) lists some of the basic properties used for level sensing as follows:

1. buoyancy,
2. cavity-resonance,
3. electrical conductivity,
4. dielectric properties,
5. heat transfer characteristics,
6. response to nuclear radiation,
7. optical properties,
8. pressure,
9. response to sound waves,
10. viscous damping effects, and
11. weight.

115

A sensor which operated on the principle of electrical resistance was introduced by the Product Engineering (1946) magazine. As the liquid made contact with the electrodes, the sensor sent a minute electric current which after amplifying controlled relays valves or pumps. Another modification in this system was the availability of sensitivity adjustment which made it possible to control chemical concentrations of liquids as well. Jones (1948) described a new type of automatic constant level controller which maintained a constant level of low boiling point liquids in a container by controlling the entry of fresh liquid from a reservoir. Regulation was performed by strong valve actuated by a vapor pressure thermometer and elastic bellows. This device had the advantage of having no external connections or relay systems. An instrument was introduced by Kovacic (1954) which, by using a sensitive spirit level mounted upon a float, accurately indicated level differences or differential air pressures. A slight change in liquid level causes a large displacement in air bubble of the level giving rise to a higher degree of sensitivity.

Williams and Maxwell (1954) designed an instrument, which operated on the capacitance principle, to measure, indicate, record, and control level of liquified gases inside a closed vessel. The sensing element was a cylindrical capacitor, whose capacitance was a function of the height of the liquid column. The measurement of capacitance was done by electrical bridge method. A four arm a.c. bridge was used for the measurement which drove a chart type recording device. They state that the chief disadvantage encountered was the need for electronic circuitry of fairly high sensitivity.

The strength of the capacitance method lies in its simplicity and adaptability. Installations have been successful even under extremely adverse conditions (Hannula 1957). He also mentioned several potential sources of error in the measurement. If the position of one electrode moves with respect to the other during the process, it causes a change in capacitance because of the change in geometry and makes the result differ from the expected. Proper mounting of probes is suggested as a remedy. He described the problem he referred to as 'hang-up'; the effect of a thin film of liquid which sticks to the electrodes when the liquid decreases after its risen to a certain level.

Capacitance level measurement requires two operations; first, the transformation of level change into capacitance change; second, the transformation of this capacitance change in to meter indication or control action. (Revesz 1958) He describes a capacitance type sensor consisting of a single metal probe at the center of a metal tank containing the liquid of which the level is to be measured. He also suggests that the rod be electrically insulated from the vessel wall due to the following disadvantages incorporated with bare probe rods. First, materials with high dielectric constants are difficult to measure, and conductive materials cannot be measured at all. Second, corrosive materials require expensive alloys to be used as rod material, thereby making long probes very costly. (Revesz 1958)

Theoretical Development

After considering all factors of interest, the capacitance type sensor was selected for further development. It was decided to build a concentric cylindrical capacitor because its geometry was best suited for installation in stilling wells. Theoretical analysis related to concentric cylindrical capacitors were carried out.

The basic property utilized in the development of this device is the higher value of dielectric constant of water than that of air. ($\varepsilon_{water} = 6.79 \times 10^{-10} Fm^{-1}$ and $\varepsilon_{air} = 8.85 \times 10^{-12} Fm^{-1}$) Using theorems on electromagnetic fields (Plonus 1978, ch.5) the expression for electrical capacitance per unit length of two concentric tubes as shown in Fig. 1 can be derived as:

$$C = \frac{2 \pi \varepsilon}{\ln \left[\dfrac{r_o}{r_i} \right]} \qquad [1]$$

where:

C = capacitance,
ε = dielectric constant of the medium,
r_o = radius of outer conductor, and
r_i = radius of inner conductor.

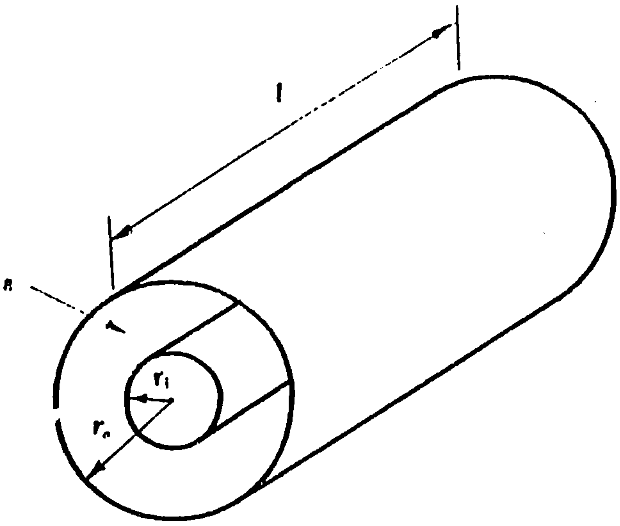

Figure 1. Concentric cylinder capacitor

If the tubes are partially submerged in one medium which has a different dielectric constant from that of the other, the total overall capacitance is given by the sum of the capacitances formed by the portion of the tubes in each medium. Referring to Fig. 2, the total capacitance can be derived as:

$$C = \frac{2\pi\varepsilon_1 l_1}{\ln\left[\frac{r_o}{r_i}\right]} + \frac{2\pi\varepsilon_2 l_2}{\ln\left[\frac{r_o}{r_i}\right]} \qquad [2]$$

where:

l_1 = submerged length in medium 1,
ε_1 = dielectric constant of medium 1,
l_2 = submerged length in medium 2, and
ε_2 = dielectric constant of medium 2.

Because water has a significantly different dielectric constant than air, a change in the submerged length of the tubes causes an overall change in capacitance of the system. This phenomena has been utilized in the development of this sensor.

Measurement of Capacitance

There are several methods in use for measuring capacitances. Whetstone bridge methods and electrical resonance methods have been used for this type of measurement. In this development, resistive charging of the capacitor was employed because it provided a simpler way of converting the capacitance change to digital form. The time delay of the output to a step change of the input of the resistor - capacitor combination was measured. By assuming the leakage resistance across the capacitor to be very large, the arrangement can be represented by the simplified circuit in Fig. 3. where a resistor and a capacitor are connected in series. The time variation of output voltage of the sensor V_o in response to a step input of V *volts* can be given as :

$$V_o = V\left[1 - e^{-t/CR}\right] \qquad [3]$$

Time, t, taken to reach a threshold voltage, V_T, is given by :

$$t = -CR \ln\left[1 - \frac{V_T}{V}\right] \qquad [4]$$

where:
R = the charging resistance.

Therefore, the measurement of time directly represents the capacitance. Based on results from preliminary investigations, it was assumed that the resistance between the cylinders remained constant for any depth of water. By combining equation [4] and equation [2], it can be shown that the relationship between the delay time, t, and the water level l_2, is linear as shown in equation [5].

$$t = -2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1)\, l_2 - 2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2) \qquad [5]$$

with the only variables being l_2 and t.

Effect of Leakage Resistance

It was assumed that the leakage resistance between the electrodes was very large. In practice it may be sufficiently low to cause a considerable change in the output. A simplified equivalent circuit could be derived by replacing the charging resistance R with its Thevenin equivalent (Edminister 1965, ch.11) R_{eq} as shown in Fig. 3. where,

$$R_{eq} = \frac{R\, R_l}{(R + R_l)} \qquad [6]$$

where:
R = charging resistance, and
R_l = leakage resistance of capacitor.

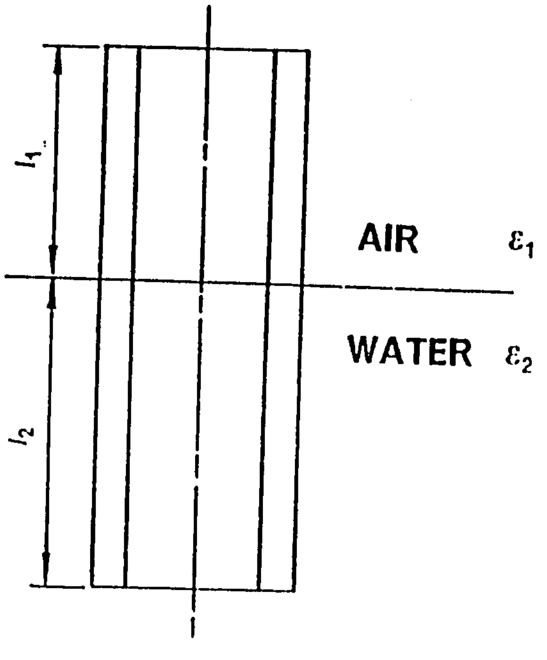

Figure 2. Partially submerged composite capacitor

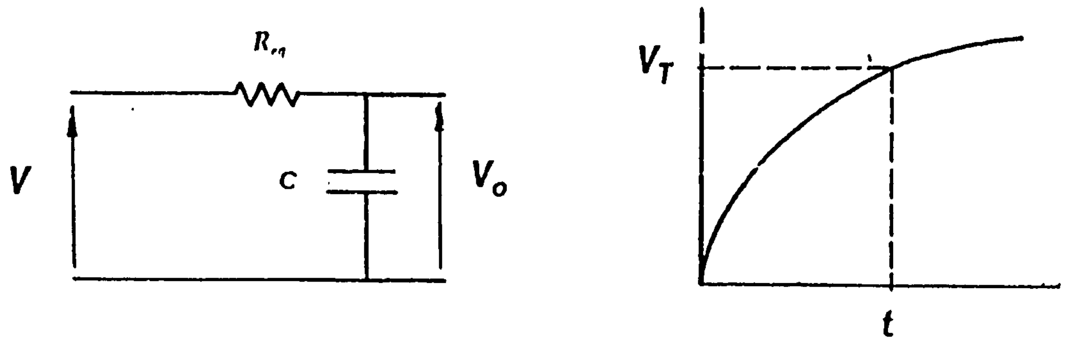

Figure 3. Simplified sensor excitation circuit and output voltage waveform

Therefore, the previous expression for delay time t could be easily modified by substituting R_{eq} for R, without changing its linear relationship to water level l_2. The modified equation is given below.

$$t = -2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1) l_2 - 2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2) \quad [7]$$

Resistance pot type sensor

Another sensor was built which made use of the same data collection technique but a different method of sensing. This development showed the versatility of the capacitance sensing method used before and resulted in another inexpensive water level sensor. The rotation of the axle of a conventional float and weight actuator was converted to a change in electrical resistance by incorporating a rotary type variable resistor (HELIPOT 10 Turn - variable resistor - 20 $k\Omega$). A fixed capacitor (0.3 μF) was connected in series with the resistor and actuated as before. The charging time was dependant on the resistor value which varied according to the water level, giving rise to another convenient way of digitizing water level data. The following linear relationship between the time delay t and water level change l was derived.

$$t = -C\left[\frac{l}{2\pi r_p}\left[\frac{R_{p_{max}} - R_{p_{min}}}{n}\right] + R_i\right] \ln\left[1 - \frac{V_T}{V}\right] \quad [8]$$

where,

t -- time delay for charging,
C = fixed capacitor,
V_T = threshold voltage,
V = excitation voltage,
R_p = resistance of the pot,
l = vertical displacement of float (water level change),
r_p = radius of pulley,
$R_{p_{max}}$ = maximum resistance of pot,
$R_{p_{min}}$ = minimum resistance of pot,
n = number of rotations of pulley, and
R_i -- initial setting of pot.

Design and Development

According to the theoretical analysis, it could be seen that the capacitance sensing technique can be used in various applications where continuous monitoring is required. As a first step factors governing the sensor design were identified for the determination of the other parameters.

Several factors had to be determined before the sensor was constructed.

1. A suitable conducting material for capacitor plates or electrodes had to be identified.
2. A method of insulating the electrodes needed to be found.
3. Height of the sensor - intended range of measurement had to be determined, and
4. Other factors which affect the sensitivity of the capacitive sensor needed to be identified.

Since the main objective in this study is to monitor water levels of irrigation canals, it was suggested that all equipment be installed in stilling wells attached to each irrigation canal. Therefore, it could be assumed that a cylindrical shape would be best suited for this particular application. Considering the wide range of sizes available, and the reasonably low cost, it was decided to use PVC drainage pipes for the construction of the two plates of the sensor. The outer surfaces of the pipes were converted to cylindrical conductors by firmly gluing a thin aluminum foil to them. Regular household aluminum wrapping foil was selected considering its extremely low cost compared to other methods such as electroplating. Electrical connections were made using aluminum wires and screws to minimize electro-chemical reactions and consequent corrosion of the foil. Selection of the cylindrical shape for the sensor capacitor was also justified by the behavior of electric field around concentric cylindrical conductors. This arrangement acts to limit the generated electric field only to the space between the tubes, when the outside conductor is at ground potential. Cylindrical shape of the tubes also matched the conventional shape of stilling wells and therefore, causes no additional difficulties in installation.

Since the capacitor is to be submerged in water, it was necessary to prevent direct leakage of current between the two electrodes. Chemical corrosion was another problem addressed in the long term use. Therefore, it was decided to insulate the electrodes against current leakages and corrosive chemical reactions.

The conductivity of insulation materials, in this case paints, played an important role in selection process. Several aluminum tubes of length 30 *cm* were painted with four different paints which were commonly available. After the suggested curing time, each of these tubes were submerged in water along with another uninsulated electrode and the resistance between the two were estimated. Two types of paint out of four, showed very high resistance to electrical current while others showed high conductivity and high leakage. After considering the appropriateness for metallic surfaces, and past experience in using the product, an Epoxy paint (PITTSBURG - Coal Tar Epoxy paint No. 97-640)[1] was selected as the best insulation for the intended application.

---

[1] Specified to describe the apparatus. No endorsement is made

For laboratory experiments and preliminary field testing applications it was decided to focus on water level fluctuations less than 39 *cm.* (1 *ft.*) Therefore, total length of capacitive sensor was made to be 39 *cm.*. At the same time, it was necessary to decide upon a suitable diameter ratio for the concentric electrodes. Equation [1] provides the basic relationship between the radii ratio r_o/r_i and capacitance C. Other important factors considered at this level were the diameter of the outer tube compared with practical sizes of stilling wells and the intermediate spacing between cylinders required for service and cleaning purposes. By taking all these into consideration, PVC pipes of diameter 7.5 *cm.* and 10.2 *cm.* (3 *in.* and 4 *in.*) were purchased. Two tubes were fixed together as a concentric cylinder capacitor, with the use of two galvanized screws and bolts. Testing was carried out with the pressure sensor which had been previously calibrated as the reference device.

Resistance pot type sensor was built by mounting a rotary type variable resistor uniaxially with a pulley. A regular float-weight combination was used to activate the setup.

The basic excitation circuit (Fig. 3) was connected and input, output voltage waveforms were observed. A digital circuit was designed to measure time delays which reflect the water level, by actuating both sensors in sequence (equation [7], [8]). After a series of tests and modifications, a microprocessor controlled data logging system was established as described below.

Digital System Design

As could be seen from the theoretical analysis, one of the major advantages of the developed sensor was that it converted water level change to a change in delay time, which could be easily measured using digital techniques. In addition to the measurement of time, the intended control system was required to issue excitation pulses to the sensor. A microprocessor based (HD64180) data logger-controller board (VITRAX Microcontroller version IX) was purchased. It consisted of a HD64180 microprocessor, an EPROM which contained BASIC (VITRAX BASIC version 3.5) system installed in it, and additional RAM space. It also had the additional features of having 24 programmable Digital I/O lines controlled through a Peripheral Interface Adapter (PIA), 56k-byte memory capacity, on-board EPROM programmer, two 16-bit programmable counter/timers, 4 external interrupts, centronics parallel printer interface, two RS-232 serial ports, and other optional facilities such as analog to digital converter.

Upon examination of the original hardware supplied, it was noticed that the power consumption is much higher than what is appropriate for a field unit. Therefore, all integrated circuits were changed to their CMOS versions in order to minimize current consumption. Furthermore, additional ICs mounted for optional tasks were completely removed.

The data logger system was operating on an EPROM based BASIC system. It was decided to change the control from BASIC to Modula-2 for several reasons such as easy input-output control and faster execution speed. A Modula-2 program was written by making the necessary additions and modifications to an existing system on a different data logger setup. This change made it possible to utilize the low power consumption mode (sleep mode) available in HD64180 processor without any difficulty. With all these software and hardware changes it was possible to reduce the average current consumption from its listed value of 175 *mA* to 12.5 *mA*.

Interface Circuit

An interface circuit was designed with an external clock generator, 16-bit binary counter, and additional logic gates. Control pulses were issued by the microprocessor through the on-board PIA and necessary logic circuits were designed to carry out counter enable/disable tasks in synchronization with processor operations. Counter output (12 bits) was read into memory through PIA ports at each excitation.

This gave rise to two additional problems. First, it increased the overall power consumption of the system and secondly, it required the addition of a separate printed circuit board attached to the data logger. Both these factors were not considered favorable for field operations. Therefore, it was decided to modify the data logging operation by utilizing the internal counter of the 64180 microprocessor, which was activated by system clock. This drastically reduced the interface circuits to one hex Schmitt trigger inverter unit for controlling both sensors. After careful examination, the

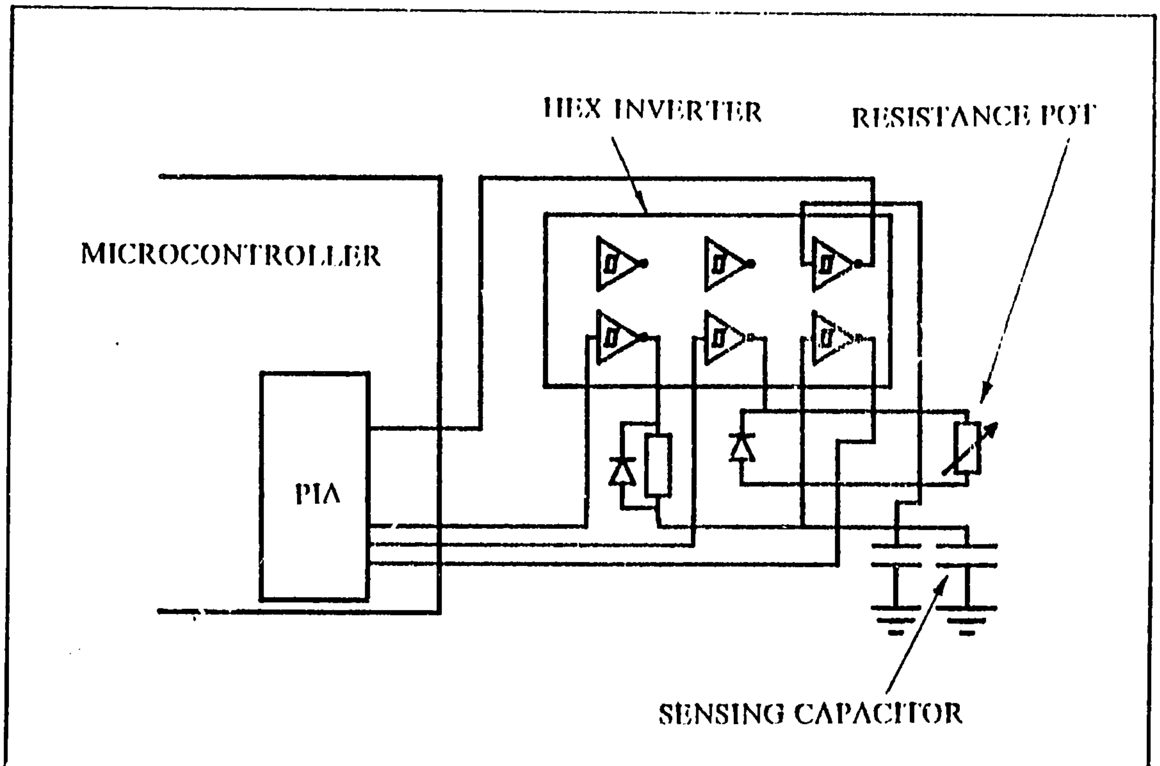

Figure 4. Schematic diagram of interface circuit and microprocessor board

inverter was installed on the microprocessor board itself, making use of its unused IC spaces. Connections to the PIA port and sensors were made using wire wrapped links. A schematic diagram is shown in Fig. 4. The developed system was tested for its proper operation and proved successful.

All software programs were written in Modula-2. The system carried out the following steps during one cycle of operation.

1. stores year, date, and time every hour on the hour,
2. updates its internal real time clock every 10 *ms*,
3. responds instantly to internal or external interrupts,
4. activates the sensors every 10 minutes in the following sequence:
    a. issues necessary control commands for proper resetting of PIA ports,
    b. loads internal counter to its high value (FFFF FFFF Hex),
    c. issues excitation pulse to sensor (capacitive type) through PIA,
    d. starts decrementing its counter,
    e. proceeds until sensor capacitor is charged to threshold level and stops decrementing upon sensing it,
    f. resets excitation pulse to neutral level,
    g. reads the internal counter and obtains the count which represents the water level, and stores it temporarily,
    h. repeats steps (b) through (g) 11 times,

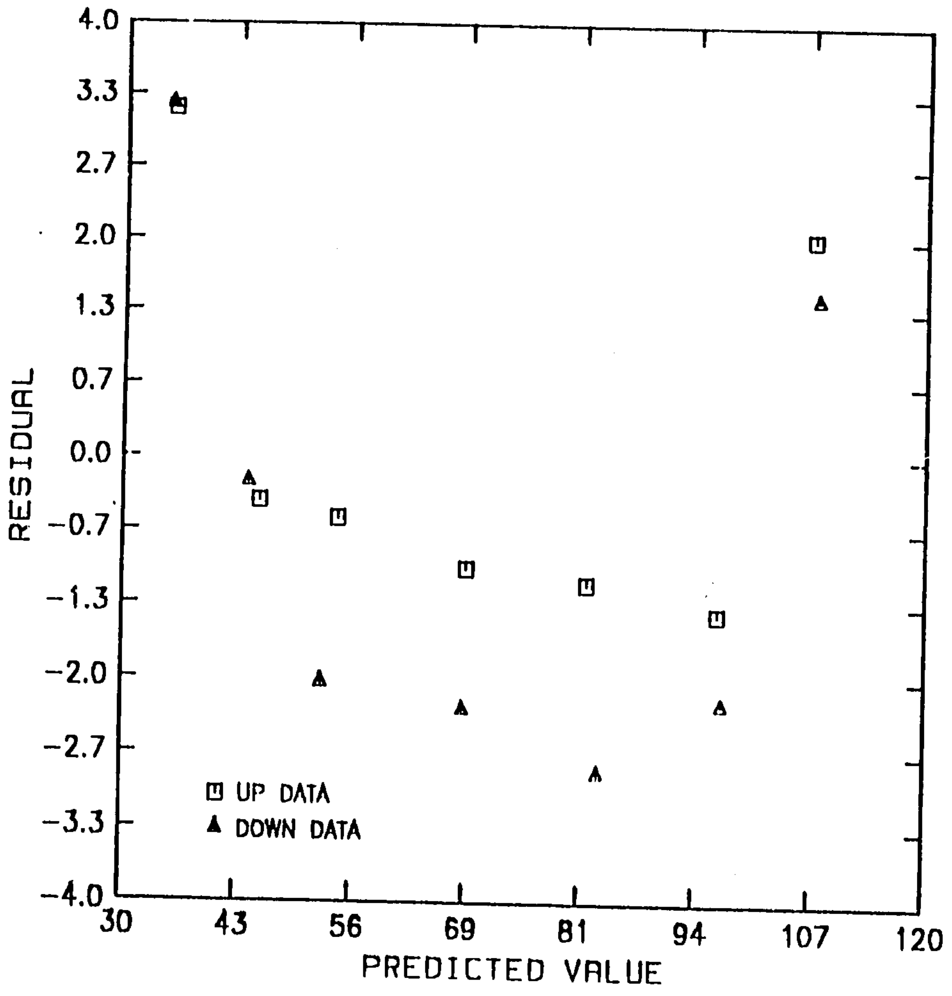

Figure 5. Plot of residuals vs. predicted values - Capacitive sensor - Equation [9]

i. computes the average and sum of squares of the last 10 data points collected (counts), (this scheme of excluding the first data point was suggested to eliminate possible error due to charges collected during the time interval between excitations)

j. if the sum of squares (SS) is less than a pre specified value, the logger stores the average,

k. if SS is higher, which shows higher variation among data points, repeats steps (b) through (i) until a satisfactory SS is obtained,

l. if SS becomes unsatisfactory for three (3) such trials, terminates excitation and stores the average of 30 data points,

m. repeats steps (a) through (l) for the other sensor (resistance pot type) and returns to sleep mode, and

5. carries out down loading of a required number of data points from storage when requested on RS-232 serial lines.

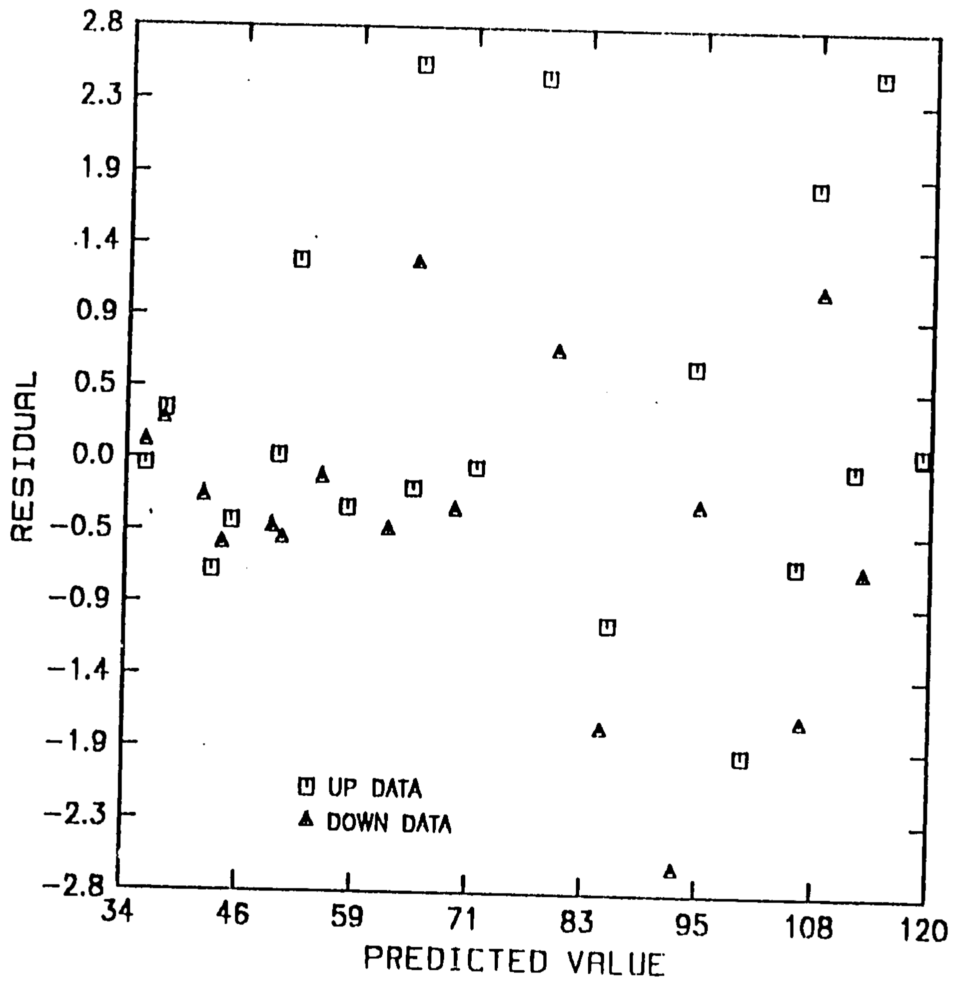

Figure 6. Plot of residuals vs. predicted values - Capacitive Sensor - Equation [10]

Experimental Procedure

The capacitor assembly and the resistance pot device were installed in a laboratory test stand, which was built with three interconnected vertical plastic sewer pipes with the facility of increasing and decreasing the water level. A commercially available pressure sensor (Sierra - Misco Model 5050LL - PTF) was installed in parallel with the new sensors and it was considered as the standard device for comparisons and calibrations. Tests were carried out with increasing and decreasing water levels, allowing a time delay to reach equilibrium at each level change. A known volume of water was added (or drained) between each reading. A settling time of 3 min was allowed after each increment of water level and it was set to 10 min for decreasing water levels. These were established after a series of experiments in which the effect of settling time on discrepancy of data points was studied (Alahakoon, Byler and Goonasekere 1988). Water level readings were recorded from each of the devices installed. To preserve the synchronization between two sensor readings, the logger was manually triggered after each level change instead of keeping it in the fully automatic real time data logging mode.

124

The time delay recorded was denoted by the variable *COUNT* in further analysis. The pressure sensor output was directly obtained by a five and a half digit digital Voltmeter and was denoted by V_p.

Results

Statistical analysis were carried out between capacitor data (*COUNT*) and pressure transducer data (V_p). A simple linear regression (equation [9]) between the pressure sensor data and capacitive sensor data resulted in an R^2 of 0.[illegible]33 and a standard error of ± 4.69 *cm* (± 0.154 *ft*).

$$V_p = A_1 + A_2\,COUNT \qquad [9]$$

On further examination of results, a prominent pattern in the residuals was observed (Fig. 5). This was suspected to be due to unaccounted variations in geometry and leakage resistance along the axis. Sharp deviations at both ends of the residual pattern could be explained as being caused by fringing of the electric field at the openings of the cylinders (end effects). In order to investigate the stability and repeatability of the sensor, the test was repeated again in the same manner. Both sets of data were combined assuming that the two experiments were identical. This was also justified by the second residual pattern being very similar to the first. Combined data set was analyzed for the purpose of establishing a model.

A nonlinear model with a second order term (equation [10]) was suggested and it provided a fairly randomly distributed residual points with a standard error of ± 1.213 *cm* (± 0.0398 *ft*).

$$V_p = A_1 + A_2\,COUNT + A_3\,COUNT^2 \qquad [10]$$

where:

$A_1 = 0.48822$,
$A_2 = 0.001304$, and
$A_3 = 0.00000125$.

The residual plot is shown in Fig. 6.

Time delay data for the resistance pot were also regressed against pressure sensor data V_p, according to equation [9]. This provided a linear fit with following coefficients and statistical parameters.

$A_1 = 0.18817$,
$A_2 = 0.002142$,
$R^2 = 0.9987$, and
standard error = ± 1.963 *cm* (± 0.0644 *ft*).

The residual pattern is shown in Fig. 7. The separation between up data and down data is due to the mechanical friction of the pulley and back-lash of the links. It was also observed that the width of the pulley used was insufficient to prevent the cord from over winding at the end.

An estimate of expenses was made on the logger and the two types of sensors. We believe that the total construction cost of the capacitive type sensor is much less than that of the resistance pot type sensor. Extensive labor cost analysis was not carried out and labor costs are not included in our extimates, shown in Table. 1.

Conclusions

It could be seen that the developed data logging system works satisfactorily. It could be used to record water level data with a standard error of ± 1.213 *cm* when used in combination with the capacitive type sensor. The resistance pot type sensor provided water level data with a standard error of ± 1.963 *cm*. The technique incorporated to convert capacitance to digital output proved to be very useful and versatile. The capacitive type sensor was less expensive to build than the resistance type and had favorable performance characteristics.

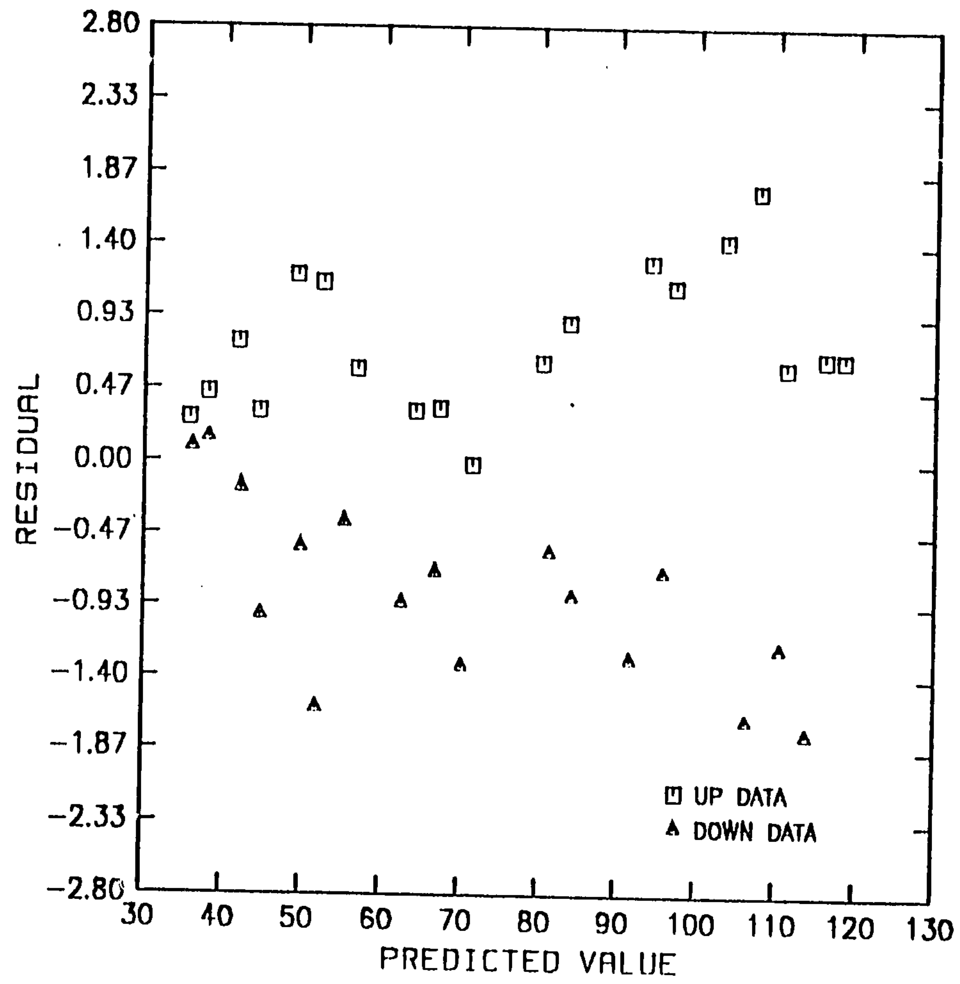

Figure 7. Plot of residuals vs. predicted values - Resistance pot - Equation [9]

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Table 1. Estimated expenses for the sensors and data logger

Item	Component name	Value ($)
Capacitive sensor	2 *m* PVC pipes	10.35
	Screws and nuts	1.00
	2 *m* aluminum wrapping foil	0.50
	Spray adhesive	1.45
	Insulating paint	2.80
Resistance pot type sensor	Variable resistor	40.00
	Pulley and fixtures	65.00
	Float, Weight and Cable	15.00
Data logger	VITRAX-IX microcontroller	140.00
	Other components	1.00

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Paper No. 893556
AN ASAE MEETING PRESENTATION

LOW COST SENSORS FOR IRRIGATION STAGE MEASUREMENT

by

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SUMMARY:

Two low cost sensors are described with a low cost digital storage system. The two systems measured water level over 1 m range. The capacitive system had a standard error of 0.4 cm and the float-resistance system had a standard error of 0.8 cm.

KEYWORDS:
Electronics, Water, Sensors, Microprocessors

American Society of Agricultural Engineers

St. Joseph, MI 49085-9659 USA

Low Cost Sensors For Irrigation Stage Measurement

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and K. G. A. Goonasekere

Introduction

Agricultural development plays a major role in the economic development of the large number of less developed countries. Major investments have been made by many governments in irrigation system development as the primary step to increase agricultural productivity. But, frequently such irrigation development initiatives have failed to produce the intended improvements in agricultural productivity due to poor management of irrigation water. Wicham and Valera (1978) mention that: 'While it is generally agreed that better water management is needed, it is not clear what is required to achieve it. What do we really mean by improved water management, how it can be attained ?'

There are manual devices for measuring and regulating water flow through canals such as weirs, flumes, and division boxes which are presently in use. There are two means by which the discharge into any distributory offtake can be controlled. The first is the regulation of the water elevation in the canal. The second is the control of gate settings at the outlet openings. But in the absence of the former, which requires proper measurement of water level, the latter becomes totally ineffective. Sophisticated devices have been built for the purpose of sensing and recording water level in such systems, but the expense has restrained them from being widely used.

The project objective is to design and build a Sensor - Data Logger unit for the improvement of water management facilities. In particular, the problem of sensing the water level in canal type irrigation systems and recording of digital data for the purpose of long term monitoring will be dealt with in this study.

Historical Background

The earliest type of level measurement can be classified as using point contact devices. In its most primitive form, a notched stick was used which provided a rough measurement of height of water above an arbitrary reference point. Man's perpetual effort to make his activities more refined and accurate, led to the design of the hook gage, point gage, and steel tape and plumb-bob gage, which make use of the same principle of measuring the distance to the top surface of reservoir from a datum. Norton (1969) lists some of the basic properties used for level sensing including buoyancy and dielectric properties.

Williams and Maxwell (1954) designed an instrument, which operated on the capacitance principle, to measure, indicate, record, and control level of liquified gases inside a closed vessel. The sensing element was a cylindrical capacitor, whose capacitance was a function of the height of the liquid column. The measurement of capacitance was done by electrical bridge method. A four arm a.c. bridge was used for the measurement which drove a chart type recording device. They state that the chief disadvantage encountered was the need for electronic circuitry of fairly high sensitivity.

The strength of the capacitance method lies in its simplicity and adaptability. Installations have been successful even under extremely adverse conditions as documented by Hannula (1957). He mentioned several potential sources of error in the measurement. If the position of one electrode moves with respect to the other during the process, it causes a change in capacitance because of the change in geometry and makes the result differ from the expected. Proper mounting of probes is suggested as a remedy. In addition, he described the problem he referred to as 'hang-up'; the effect of a thin film of liquid which sticks to the electrodes when the liquid decreases after its risen to a certain level.

Capacitance level measurement requires two operations, first, the transformation of level change into capacitance change; second, the transformation of this capacitance change into a meter indication or control action (Revesz, 1958). He describes a capacitance type sensor consisting of a single metal probe at the center of a metal tank containing the liquid of which the level is to be measured. He also suggests that the rod be electrically insulated from the vessel wall due to disadvantages incorporated with bare probe rods.

Theoretical Development

After considering all factors of interest, the capacitance type sensor was selected for further development. It was decided to build a concentric cylindrical capacitor because its geometry was best suited for installation in stilling wells. Theoretical analysis related to concentric cylindrical capacitors were carried out.

The basic property utilized in the development of this device is the higher value of dielectric constant of water than that of air ($\varepsilon_{water} = 6.79x10^{-10}Fm^{-1}$ and $\varepsilon_{air} = 8.85x10^{-12}Fm^{-1}$). Using theorems on electromagnetic fields (Solymar, 1984, ch.2) the expression for electrical capacitance per unit length of two concentric tubes is:

$$C = \frac{2\pi\varepsilon}{\ln\left[\frac{r_o}{r_i}\right]} \qquad [1]$$

where:
C = capacitance,
ε = dielectric constant of the medium,
r_o = radius of outer conductor, and
r_i = radius of inner conductor.

If the tubes are partially submerged in one medium which has a different dielectric constant from that of the other, the total overall capacitance is given by the sum of the capacitances formed by the portion of the tubes in each medium. Referring to Fig. 1, the total capacitance can be derived as:

$$C = \frac{2\pi\varepsilon_1 l_1}{\ln\left[\frac{r_o}{r_i}\right]} + \frac{2\pi\varepsilon_2 l_2}{\ln\left[\frac{r_o}{r_i}\right]} \qquad [2]$$

where:
l_1 = submerged length in medium 1,
ε_1 = dielectric constant of medium 1,
l_2 = submerged length in medium 2, and
ε_2 = dielectric constant of medium 2.

Because water has a significantly different dielectric constant than air, a change in the submerged length of the tubes causes an overall change in capacitance of the system. This phenomena has been utilized in the development of this sensor.

Measurement of Capacitance

There are several methods in use for measuring capacitances. Whetstone bridge methods and electrical resonance methods have been used for this type of measurement. In this project resistive charging of the capacitor was employed because it provided a simpler way of converting the capacitance change to digital form. The time delay of the output to a step change of the input of the resistor - capacitor combination was measured. By assuming the leakage resistance across the capacitor to be very large, the arrangement can be represented by the simplified circuit in Fig. 2. where a resistor and a capacitor are connected in series. The time variation of output voltage of the sensor V_o in response to a step input of V *volts* can be given as :

$$V_o = V\left[1 - e^{-t/CR}\right] \qquad [3]$$

Time, t, taken to reach a threshold voltage, V_t is given by :

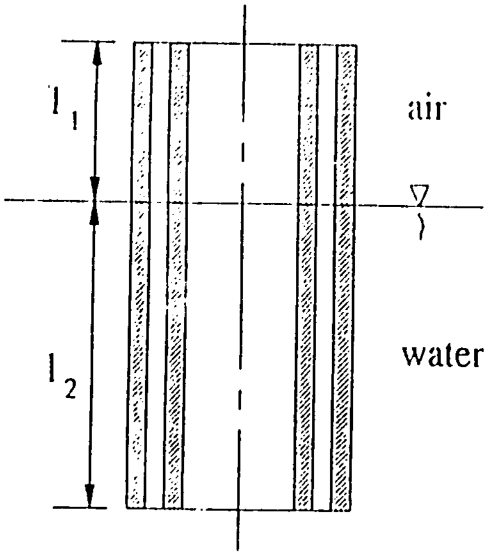

Figure 1. Partially submerged composite capacitor

$$t = -CR \ln\left[1 - \frac{V_T}{V}\right] \qquad [4]$$

where:
R = the charging resistance.

Therefore, the measurement of time directly represents the capacitance. Based on results from preliminary investigations, it was assumed that the resistance between the cylinders remained constant for any depth of water. By combining equation [4] and equation [2], it can be shown that the relationship between the delay time, t, and the water level l_2, is linear as shown in equation [5].

$$t = -2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1)\, l_2 - 2\pi R \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2) \qquad [5]$$

with the only variables being l_2 and t.

Effect of Leakage Resistance

It was assumed that the leakage resistance between the electrodes was very large. In practice it may be sufficiently low to cause a considerable change in the output. A simplified equivalent circuit was derived by replacing the charging resistance R with its Thevenin equivalent (Edminister 1965, ch.11) R_{eq} as shown in Fig. 2. where,

$$R_{eq} = \frac{R\,R_l}{(R + R_l)} \qquad [6]$$

where:
R = charging resistance, and
R_l = leakage resistance of capacitor.

Therefore, the previous expression for delay time t was modified by substituting R_{eq} for R, without changing its linear relationship to water level l. The modified equation is given below

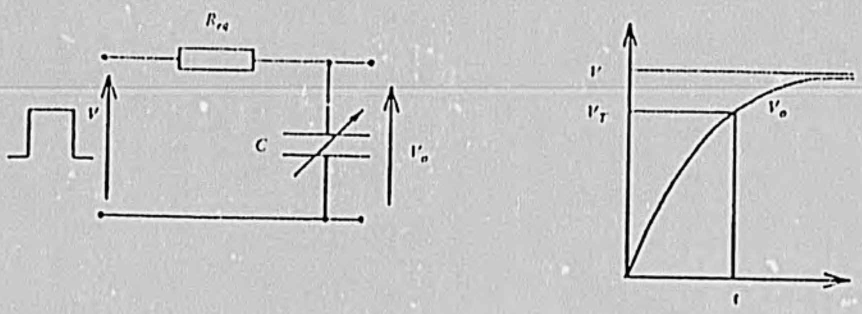

Figure 2. Simplified sensor excitation circuit and output voltage waveform

$$t = -2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} (\varepsilon_2 - \varepsilon_1) l_2 - 2\pi R_{eq} \frac{\ln\left[1 - \frac{V_T}{V}\right]}{\ln\left[\frac{r_o}{r_i}\right]} \varepsilon_1 (l_1 + l_2) \quad [7]$$

Resistance potentiometer type sensor

Another sensor was built which made use of the same data collection technique but a different method of sensing. The rotation of the axle of a conventional float and weight actuator was converted to a change in electrical resistance by incorporating a rotary type variable resistor (HELIPOT 10 Turn - variable resistor - 20 $k\Omega$). A fixed capacitor (0.3 μF) was connected in series with the resistor and actuated as before. The charging time was dependant on the resistor value which varied according to the water level, giving rise to another convenient way of digitizing water level data. The following linear relationship between the time delay t and water level change l was derived.

$$t = -C\left[\frac{l}{2\pi r_p}\left[\frac{R_{p_{max}} - R_{p_{min}}}{n}\right] + R_i\right] \ln\left[1 - \frac{V_T}{V}\right] \quad [8]$$

where,

t = time delay for charging,
C = fixed capacitor,
V_T = threshold voltage,
V = excitation voltage,
R_p = resistance of the pot,
l = vertical displacement of float (water level change),
r_p = radius of pulley,
$R_{p_{max}}$ = maximum resistance of pot,
$R_{p_{min}}$ = minimum resistance of pot,
n = number of rotations of pulley, and
R_i = initial setting of pot.

Design and Development

According to the theoretical analyses, it could be seen that the capacitance sensing technique can be used in various applications where continuous monitoring is required. As a first step factors governing the sensor design were identified for the determination of the other parameters.

Several factors were determined before the sensor was constructed.

1. A suitable conducting material for capacitor plates or electrodes was identified.
2. A method of insulating the electrodes was developed.
3. Height of the sensor - intended range of measurement was determined, and
4. Other factors which affect the sensitivity of the capacitive sensor were identified.

Because the main objective in this study was to monitor water levels of irrigation canals, it was suggested that all equipment be installed in stilling wells attached to each irrigation canal. Therefore, a cylindrical shape would be suited for this particular application. Considering the wide range of sizes available, and the reasonably low cost, it was decided to use PVC drainage pipes for the construction of the two plates of the sensor. The outer surfaces of the pipes were converted to cylindrical conductors by firmly gluing thin aluminum foil to them. Regular household aluminum wrapping foil was selected considering its low cost compared to other methods, such as electroplating. Electrical connections were made using aluminum wires and screws to minimize electro-chemical reactions and consequent corrosion of the foil. Selection of the cylindrical shape for the sensor capacitor was also justified by the behavior of electric field around concentric cylindrical conductors. This arrangement acts to limit the generated electric field only to the space between the tubes, when the outside conductor is at ground potential.

Because the capacitor was to be submerged in water, it was necessary to prevent direct leakage of current between the two electrodes. Chemical corrosion was another problem addressed in long term use. Therefore, it was decided to insulate the electrodes against current leakages and corrosive chemical reactions. After considering the appropriateness for metallic surfaces, some testing, and past experience in using the product, an Epoxy paint (PITTSBURG - Coal Tar Epoxy paint No. 97-640) [1] was selected as the best insulation for the intended application.

For laboratory experiments and preliminary field testing applications it was decided to focus on water level fluctuations less than 1 *m*. Capacitive sensors with a total active length of 99 *cm* were constructed. At the same time, it was necessary to decide upon a suitable diameter ratio for the concentric electrodes. Equation [1] provides the basic relationship between the radii ratio r_o/r_i and capacitance C. Other important factors considered were the diameter of the outer tube compared with practical sizes of stilling wells and the intermediate spacing between cylinders required for service and cleaning purposes. By taking all these into consideration, PVC pipes of diameter 7.5 *cm* and 10.2 *cm* (3 *in* and 4 *in*) were purchased. Two tubes were fixed together as a concentric cylinder capacitor, with the use of two galvanized screws and bolts. Testing was carried out with the pressure type stage sensor which had been previously calibrated.

The resistance pot type sensor was built by mounting a rotary type variable resistor uniaxially with a pulley. A regular float-weight combination was used to activate the setup. The basic excitation circuit (Fig. 2) was connected to both sensors and input, output voltage waveforms were observed. A digital circuit was designed to measure time delays which reflect the water level, by actuating both sensors in sequence. After a series of tests and modifications, a microprocessor controlled data logging system was established as described below.

Digital System Design

As could be seen from the theoretical analysis, one of the major advantages of the developed sensors was that it converted water level change to a change in delay time, which could be easily measured using digital techniques. In addition to the measurement of time, the intended control system needed to issue excitation pulses to the sensor. A microprocessor based data logger-controller board (VITRAX Microcontroller version IX)[2] was purchased. It consisted of a HD64180 microprocessor, an EPROM which contained BASIC system installed in it, and additional RAM space. It also had additional features of: 24 programmable digital I/O lines controlled through a Peripheral Interface Adapter (PIA), 56k-byte memory capacity, on-board EPROM programmer, two 16-bit

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[1] Specified to describe the apparatus No endorsement is made

[2] Specified to describe the apparatus. No endorsement is made

programmable counter/timers, 4 external interrupts, centronics parallel printer interface, and two RS-232 serial ports.

Upon examination of the original hardware supplied, it was noticed that the power consumption was much higher than what is appropriate for a field unit. Therefore, all integrated circuits were changed to their CMOS versions in order to minimize current consumption. Furthermore, additional ICs not needed for this application were completely removed.

The data logger system was operating on an EPROM based BASIC system. It was decided to change the control from BASIC to Modula 2 for several reasons such as easier input-output control, faster execution speed, and ease of management with several people working on the code. A Modula-2 program was written by making the necessary additions and modifications to an existing system on a different data logger setup. This change made it possible to utilize the low power consumption mode (sleep mode) available in HD64180 processor without any difficulty. With all these software and hardware changes it was possible to reduce the average current consumption from its listed value of 175 *mA* to 12.5 *mA*.

Interface Circuit

The internal counter of the HD64180 microprocessor, was used to measure time. This reduced the interface circuits to one hex Schmitt trigger inverter unit for controlling two sensors. After careful examination, the inverter was installed on the microprocessor board itself, making use of an IC space. Connections to the PIA port and sensors were made using wire wrapped links. A schematic diagram is shown in Fig. 3. The developed system was tested for its proper operation and proved successful.

All software programs were written in Modula-2. The system carried out the following steps during one cycle of operation:

1. stores year, date, and time every hour on the hour,
2. updates its internal real time clock every 10 *ms*,
3. responds instantly to internal or external interrupts,
4. activates the sensors every 10 minutes in the following sequence:
    a. issues necessary control commands for proper resetting of PIA ports,
    b. loads internal counter to its high value (FFFF FFFF Hex),
    c. issues excitation pulse to sensor (capacitive type) through PIA,
    d. starts decrementing its counter,
    e. proceeds until sensor capacitor is charged to threshold level and stops decrementing upon sensing it,
    f. resets excitation pulse to neutral level,
    g. reads the internal counter and obtains the count which represents the water level, and stores it temporarily,
    h. repeats steps (b) through (g) 11 times,
    i. computes the average and sum of squares of the last 10 data points collected (counts), (this scheme of excluding the first data point was suggested to eliminate possible error due to charges collected during the time interval between excitations)
    j. if the residual sum of squares (SS) is less than a prespecified value, the logger stores the average,
    k. if SS is higher, which shows higher variation among data points, repeats steps (b) through (i) until a satisfactory SS is obtained.

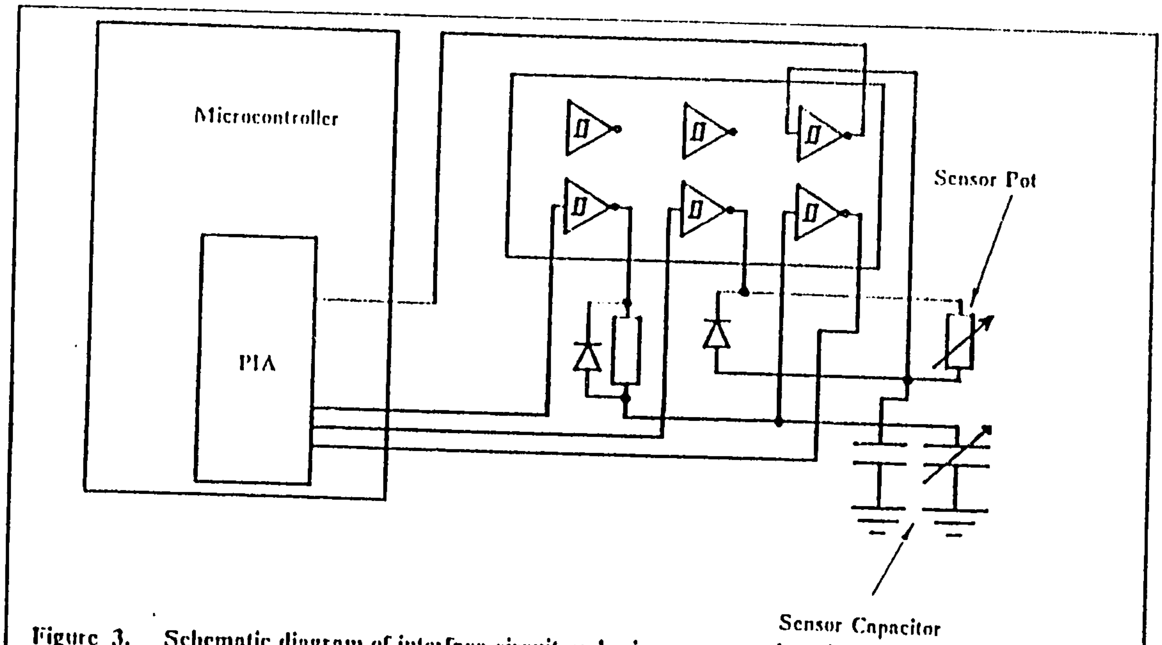

Figure 3. Schematic diagram of interface circuit and microprocessor board

l. if SS becomes unsatisfactory for three (3) such trials, terminates excitation and stores the average of 30 data points,

m. repeats steps (a) through (l) for the other sensor (resistance pot type) and returns to sleep mode, and

5. carries out down loading of a required number of data points from storage when requested on RS-232 serial lines.

Experimental Procedure

The capacitor assembly and the resistance pot device were installed in a laboratory test stand, which was built with three interconnected vertical plastic sewer pipes with the facility of increasing and decreasing the water level. A commercially available pressure sensor (Sierra - Misco Model 5050LL - PTF)[1] was installed in parallel with the new sensors and it was considered as the standard device for comparisons and calibrations. Tests were carried out with increasing and decreasing water levels, allowing a time delay for the equipment to reach equilibrium at each level change. A known volume of water was added (or drained) between each reading. A settling time of 3 min was allowed after each increment of water level and it was set to 10 min for decreasing water levels. These were established after a series of experiments in which the effect of settling time on discrepancy of data points was studied (Alahakoon, Byler and Goonasekere 1988). Water level readings were recorded from each of the devices installed. To preserve the synchronization between two sensor readings, the logger was manually triggered after each level change instead of keeping it in the fully automatic real time data logging mode.

The recorded time delay was denoted by the variable *COUNT* in further analysis. The pressure sensor output was directly obtained by a five and a half digit digital Voltmeter and was converted to centimetres (*cm*). It is denoted by *L* in the following analysis.

Statistical analysis were carried out between capacitor data (*COUNT*) and pressure transducer data (*L*). A simple linear regression between the pressure sensor data and capacitive sensor data

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[1] Specified to describe the apparatus. No endorsement is made

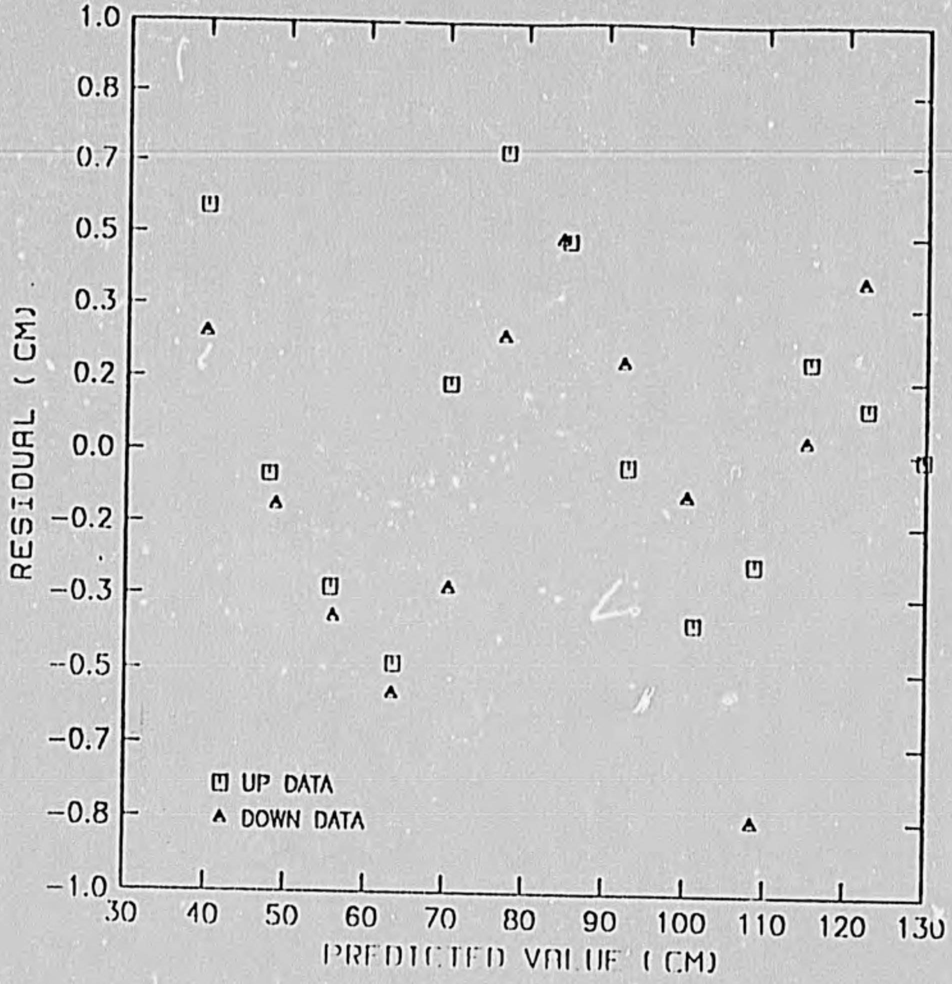

Figure 4. Plot of residuals vs. predicted values - Capacitive Sensor - Equation [9]

produced the residual pattern shown in Fig. 4 and R^2 of 0.9998 and a standard error of ± 0.39 *cm* and resulted in the equation:

$$L = 35.95 + 0.0539\,COUNT. \qquad [9]$$

Performance of the modified sensor was better than the previously developed models (Alahakoon, 1989 and Alahakoon, Byler and Goonasekere, 1988). The same test was carried out again under the same conditions, and analysis of combined data proved that sensor performance was stable over repeated tests (Fig. 5). Even though there was a pattern in residuals, the error was neglected because the overall standard error was small. The pattern which still remained was assumed to be due to irregularities in paint thickness. The overall sensitivity was found to be 18 *COUNTS* per *cm* and standard error of the prediction by the model was ± 0.4 *cm*.

Problems encountered in constructing the sensor which could cause small errors in the measurement were gluing the aluminum foil to the PVC pipe uniformly and painting. Aluminum foil was very easily wrinkled during the process of gluing and provided an irregular surface. The remaining wrinkles were firmly hand pressed using a smooth, hard surface. Painting was done manually with a regular paint brush. Because the conducting aluminum layers were attached only to outer surfaces,

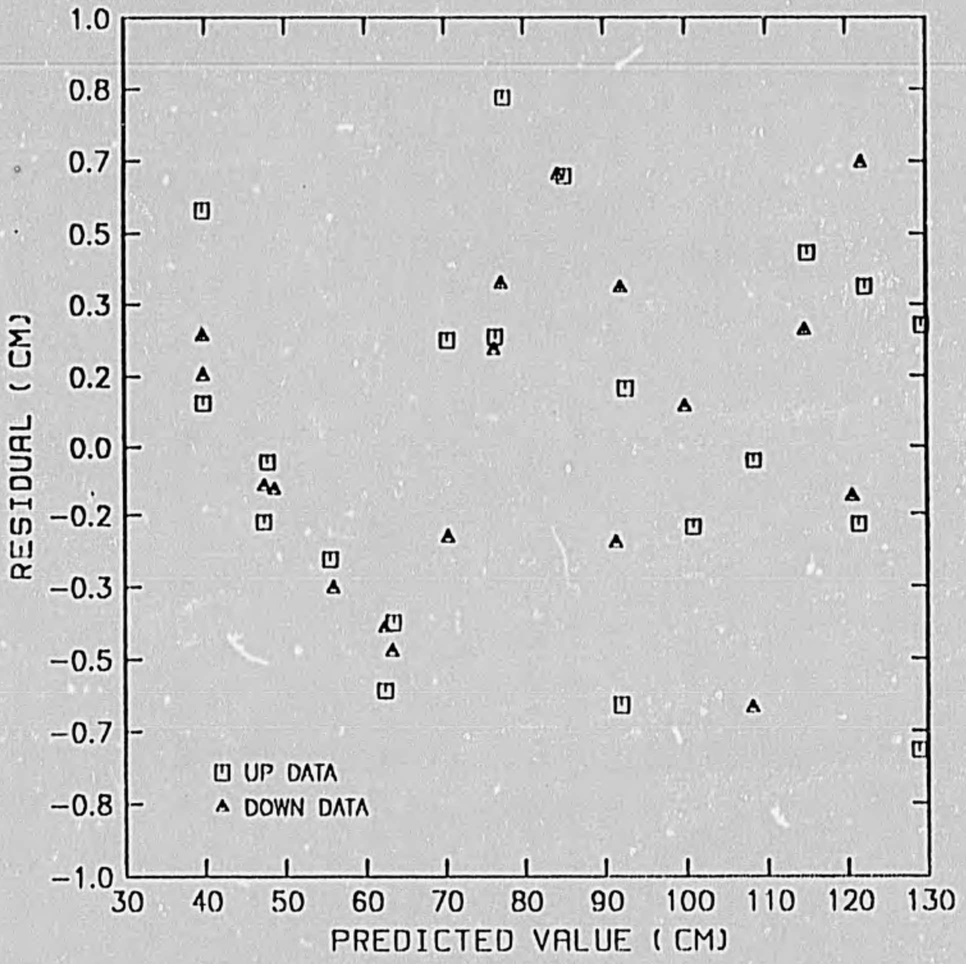

Figure 5. Plot of residuals vs. predicted values - Capacitive Sensor (Two Tests Combined)

of both PVC pipes, it wasn't necessary to insulate the inside surfaces. The thickness and the surface finish of the PVC pipes were assumed to be sufficiently uniform. Due to the high viscosity of the paint, it was difficult to obtain a uniform thickness over the whole surface.

Considering the factors affecting the performance of the capacitor, it could be hypothesized that water temperature and salinity are two parameters which may have an influence on the sensor characteristics in varying environmental conditions. Six sets of data were collected to determine if water temperature or salinity would affect the device. The first two sets were simply repeat sets of data. The third and fourth had water temperature 5 degrees C warmer and colder than for the first two test. For the fifth test 25g of sodium chloride was added to the 50 l of water which was used in the test and for the sixth test an additional 100 g of sodium chloride was added.

Analyses were performed on the resulting data with one intercept (the difference in the water depth datums for the two sensors) and 6 different fitted slopes. The standard error for straight line fits to all six data sets using a commom intercept was 0.49 cm, or the same as before. When a common intercept and a common slope was used for all six data sets the standard error was 2.5 cm, and there were clear patterns in the residuals. The data with water of different temperatures was clearly dif-

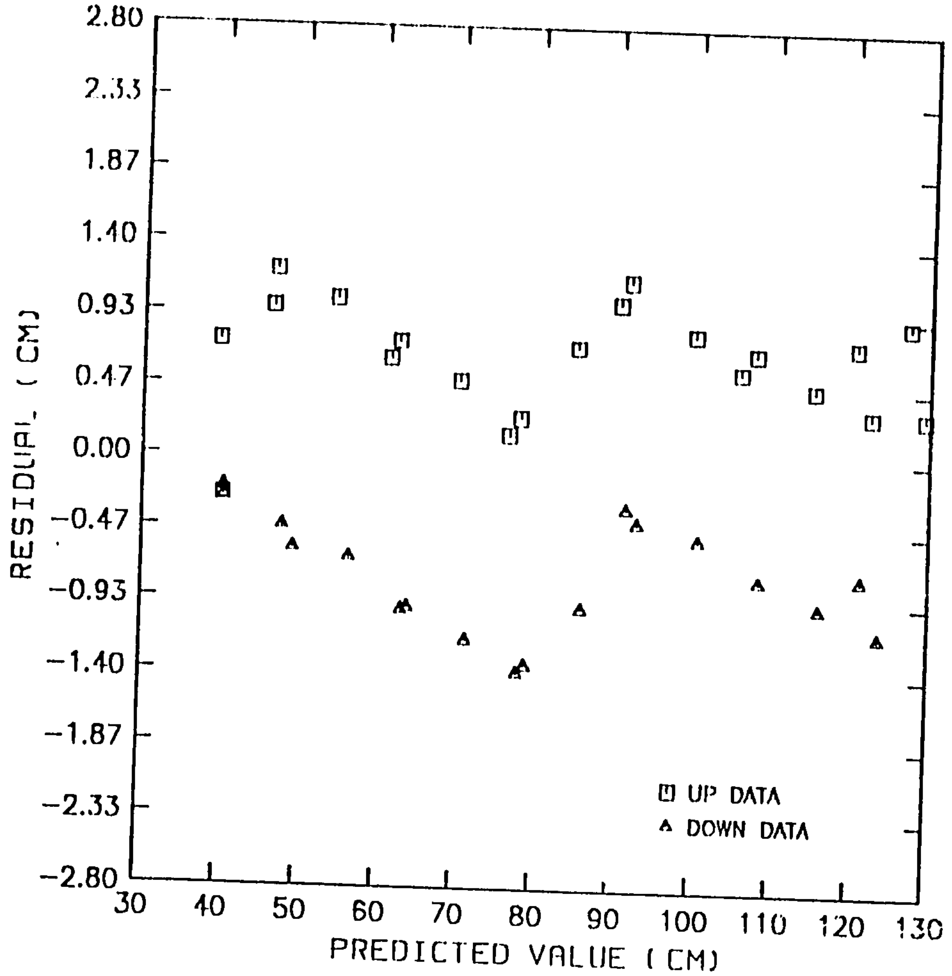

Figure 6. Plot of residuals vs. predicted values - Resistance pot - Equation [10]

ferent than that from the first two sets. The slope of the time delay - water depth line was significantly lower at the higher temperature and higher at the lower temperature. The affect of adding salt to the water was inconclusive, with a trend toward lower slope for higher salt concentrations. Insufficient data were collected to support stronger conclusions.

Further work is planned, a short reference capacitor section will be formed which will always be submerged. The water stage will be calculated in reference to the known depth in the submerged section.

Time delay data for the resistance pot were also regressed against pressure sensor data V_p, according to equation [8]. This provided a linear fit with following coefficients and statistical parameters:

$$L = 19.385 + 0.0695\,COUNT \qquad [10]$$

with R^2 of 0.9992, and a standard error of $\pm$ 0.82 cm.