VIRTUAL TECHNIQUES FOR LIQUID LEVEL MONITORING USING DIFFERENTIAL PRESSURE SENSORS

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Abstract. The purpose of presented paper is to demonstrate an innovative approach for low cost continuous liquid level monitoring based on virtual instrumentation. Most of the traditional measuring systems were designed and implemented by complicated hardware circuitry. It made the product expensive, with low functionality and with limited precision. With virtual measurement technology, more of the instrument can be substituted by software. Using this approach the cheaper and more versatile measurement system can be developed. As introduction in order to select an appropriate method for liquid level monitoring the comparative analysis of more popular technologies is done. The method for obtaining both liquid density and liquid level with two differential pressure sensors is suggested and considered. Some basic considerations about the modern integrated pressure sensors and some aspects concerning their capability for liquid level measurement are done. Finally, a prototype of a liquid level monitoring system based on integrated differential pressure sensors, multifunction data acquisition board and LabVIEW environment is developed for measuring liquid level accurately at distances up to 10 metres. In order to illustrate flexibility of the designed system the front panel of the developed virtual instrument is presented. Measurements carried out in laboratory show that the accuracy of some millimetres could be achieved.

Keywords: virtual instrumentation, level measurement, monolithic pressure sensors, data acquisition, LabVIEW

1. Introduction

Many industrial and scientific processes require knowledge of the quantity of content of tanks and other containers. In many instances it is not possible or not practical to directly view the interior. The more obvious industrial applications include:

– tank level gauging of milk, beer or wine in food and beverage industry;

– levels and contents gauging of acid, oil and solvent vessels in chemical plants;

– level monitoring of water in reservoirs;

– water flow monitoring for leak detection for smart and industrial washing machines.

Parameters of interest are generally: level of the contents, liquid density, volume, temperature and rate of level change. For many of applications is desirable continuous measurement and monitoring of these parameters.

Level measurement for liquids can be accomplished with over 20 different technologies being offered on the market today [1, 2, 3]. With the wide variety of approaches identifying the right one for specific application can be very difficult.

Many applications require a single tank to process multiple environments with different densities or they have a media that changes density with temperature. This is very common in the food and beverage industry where different ingredients are blended and mixed in the same tanks. An accurate liquid level measurement in these conditions utilizing a gage type instrument mounted in the base of the tank is impossible. Continuous liquid level measurement and the detection of both density and temperature of liquids with dissimilar properties are classical topics in level sensor research. Several solutions have been developed that rely on a variety of working principles [1]. Some of these solutions, such as those based on pressure or density measurements, involve the use of mobile parts or the opening of extra outlets in the tank or vessel, and their results are often affected by temperature or density variations [3]. Other solutions based on the measurement of wave propagation times overcome most of these drawbacks but also have their own limitations, in particular signal attenuation in conductive media and the need for measuring additional electrical parameters in the case of two-phase media such as oil and water [2]. Some of the most commonly used liquid level and density measurement methods suitable for continuous monitoring are summarized in table 1.

Over the last several decades, computer control of manufacturing systems has been the focus of extensive research. Advances in microprocessor, computing, networking and interfacing technologies have improved capabilities of industrial measurement and monitoring systems substantially over this period. The development of virtual and open architecture monitoring systems shift the focus of automation from being hardware centric to software centric, providing further flexibility [4].

Table 1. Comparison between different methods for continuous liquid level measurement

Method/ Sensor	Advantages	Disadvantages
Emerging Technologies (Time-of-Flight Measurements)		
Ultrasonic/Sonic	Easy to install; Non-contact measurement; No moving parts; Can measure corrosive and volatile liquids	Need high power; Low accuracy; Not operate on vacuum or high pressure applications; Expensive; Temperature correction is needed
Laser Level Transmitters	Use in vessels with numerous obstructions; High level of accuracy (better than 1 mm)	Expensive; Fails if dust, smoke, etc. are present in the vessel; Sensitive to dirt
Radar (Microwaves) Level Transmitters	Non-contact measurement; The transmission time is unaffected by ambient temperature and pressure fluctuations (can be used in closed tanks, where the liquid is turbulent and in the presence of obstructions and steam condensate)	Internal piping and multiple reflections can cause erroneous readings; Transmitter setup can be tedious and changes in the process environment can be problematic; The appropriate licences have to be obtained
Level measurement by hydrostatic pressure		
Bubbler-type sensor	Simplicity of design; Low initial purchase cost	Not suitable for use in non-vented vessels; Used gas may affect the contents of the tank
Differential Pressure Silicon Sensors	Inexpensive, Wide range measurements; Can be isolated safely from the process; Measurements can be digitally networked for remote computer access	Need power and active electronic; Require two vessel penetrations; Depends on the density and the temperature of the liquid
Level Measurements by Detecting Electrical Properties		
Capacitance level transmitters	Suitable for use in extreme conditions; Only a single tank penetration is required	Large errors caused by coatings; Normally limited to water-like media; Temperature correction is needed
RF Capacitance	Wide range of process conditions; No moving parts; Only a single tank penetration; Easy to use, Simple to clean	Special considerations is needed, to minimize errors caused by probe movement; Specific circuitry is needed
Up thrust buoyancy (Float systems)		
Displacers/Floats	The only available technique for a cryogenic application; Adaptable to wide variations in fluid densities	Only for relatively clean fluids; High installation cost; Depends on the specific gravity of the liquid; Temperature correction is needed
Magnetostrictive Sensor	High level of accuracy; Reliable and repeatable; Non-contact; Low maintenance cost; Wide operating temperature range; Low and stable offset and low sensitivity to mechanical stress	Can work only if the auxiliary column and chamber walls constructed by nonmagnetic material; Magnets must not be operated beyond their Curie point

The software defined nature of virtual instrumentation brings several benefits to engineers and scientists. Only with virtual measurement technology they can create the user-defined instruments that nimbly adapt to measure various physical phenomena. Engineers can modify the software to add new functionality or support new devices, and the modular hardware can be rapidly combined in any order or quantity to perform any task required. With this approach, the users can quickly create custom hardware circuitry with high-performance input/output and unprecedented flexibility in system timing control without actually building custom circuitry.

The goal of the presented investigation is to develop a virtual system for continuous liquid level measurement and monitoring of various liquids. The designed system is based on measurement method for liquid level and density detection by hydrostatic pressure. The measurement technique uses integrated differential pressure sensors, portable multifunction data acquisition board and graphical programming environment.

2. Hydrostatic pressure and level sensing theory

There are three types of pressure measurement. Absolute pressure does include atmospheric pressure, and is measured relative to vacuum. Differential pressure is the difference between two pressures. Gage pressure is a form of differential pressure measurement in which atmospheric pressure is used as the reference.

A pressure transmitter can be used to determine the liquid level in a tank, well, river or other body of liquid [3]. If a pipe is placed vertically, with one end dipped into a liquid and the upper end of the pipe is closed off and some air volume is trapped, the pressure in the pipe will vary proportionally with the liquid level change in the tank or vessel. A gauge pressure sensor has one side connected to the pipe (pressure side) and the other side open to ambient (in this case, atmospheric) pressure. The sensor measures the pressure difference, which corresponds to the change in the tank level.

Therefore, the hydrostatic pressure depends on the air pressure, the fluid density and the height of the column of fluid and can be expressed:

$$P = P_{atm} + \rho \cdot g \cdot h, \quad (1)$$

where P is pressure, in Pa, P_{atm} is atmospheric pressure, in Pa, ρ is mass density of fluid, in kg/m^3, g is standard gravity 9.8066 m/s^2, and h is height of fluid column, in m.

The mass density ρ for a homogeneous object is defined as the ratio of its mass m to its volume V. Instead mass density when measuring liquid level, the term specific gravity frequently is used to describe the weight or density of a liquid compared to an equal volume of fresh water at 4°C. It is therefore a dimensionless quantity. A higher or lower specific gravity can have a considerable impact on level measurement.

In this paper is suggested method for obtaining both liquid density and level using two differential pressure sensors. The method is suitable either for vented or closed tank and vessels. As shown in the figure 1 mounting the two pipes of a differential pressure sensor DP1 a known distance h_{ref} apart will measure the hydrostatic head pressure between these two points:

$$\Delta P_1 = \rho \cdot g \cdot h_{ref} \quad (2)$$

Since h_{ref} is known, the mass density of the media is.

$$\rho = \frac{\Delta P_1}{g \cdot h_{ref}} \quad (3)$$

A differential pressure sensor DP2 with the high side running to the base of the tank and the low side plumbed to the top of the tank above the liquid will measure the difference ΔP_2 between the gas pressure (atmospheric pressure P_{atm} if tank is vented) and the combined gas and liquid level pressure. To calculate the liquid height, can be used the measured pressure with the following equation:

$$h = \frac{\Delta P_2}{g \cdot \rho} = \frac{\Delta P_2}{\Delta P_1} \cdot h_{ref}\,. \quad (4)$$

As can be considered by equation (4), utilizing two differential pressure sensors will provide an accurate liquid level measurement even if the density is changing. Because the density of an object depends on its temperature, the thermocouple is provided to monitor temperature T during measurement process.

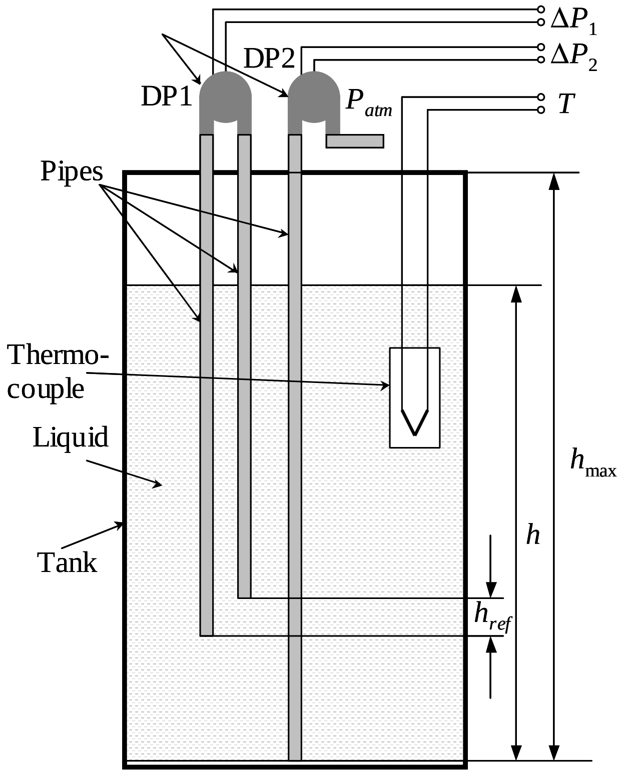

Figure 1. Mounting of the two differential pressure sensors and the thermocouple

3. Virtual system design and consideration

3.1. Pressure sensor selection

Back in the days of mechanical, analogue pressure gages, most designs were variations on one basic approach. However, with the shift to electronic sensors, a completely new group of measuring technologies emerged. Micro Electro Mechanical Systems (MEMS) are generally considered as micro systems consisting of micro mechanical sensors, actuators and micro electronic circuits. One of the most commercially successful MEMS technologies is the pressure sensor. Silicon pressure sensors are available that measure pressure ranges from around one to several thousand kPa, with resolutions as fine as 100 ppm.

In this paper utilizing of the integrated piezoresistive MEMS sensors is proposed. These monolithic fully signal conditioned sensor offers many advantages when used in various applications. They provide high accuracy, wide operating temperature range, high reliability, and a relatively low cost. Usually the sensors operate from a 5 V supply and have a linear output from 0.5 V to 4.5 V providing a direct interface to an analogue inputs of data acquisition boards [5]. Unlike discrete devices, the monolithic sensor requires no additional interface circuitry to perform the output signal function. Although the price of a single chip fully compensated sensor is somewhat higher than a discrete sensor, monolithic pressure sensor is more cost effective when the entire system is considered.

A number of manufacturers have developed a piezoresistive pressure sensor family, which is very well adapted for level sensing, especially when using an air pipe sensing method [5, 6, 7]. Fully signal conditioned single chip pressure sensors are available in ranges from 4 kPa to 700 kPa. The pressure range is determined by the minimum and maximum altitude the system will be expected to operate over. This means that the engineers are able to design the systems as for low liquid height (up to 0.4 m with 1 mm resolution) as for large tanks (up to 72 m with 60 mm resolution). These devices are fully interchangeable within the set pressure range.

The ideal transfer function for integrated differential pressure sensor is:

$$V_{DP} = V_S\,(\Delta P \cdot S + N)\,, \qquad (5)$$

where S is the sensitivity, V_S is supply voltage, ΔP is differential pressure and N is the null set point. The transfer function is specified for a referenced voltage V_S that give opportunity for ratiometric measurement [8]. In contrast of absolute measurement, a ratiometric measurement provides a result that is the ratio of the reference voltage.

In process of design, it is important to define the parameters necessary to describe a pressure sensor. Parameters of interest for high accuracy sensor designs are: linearity, ratiometricity, stability, repeatability, hysteresis, null set point, span set point and null temperature shift. In order to measure pressure difference in liquids the dual port case sensors should be selected as well.

3.2. Choice of measurement hardware

The design of proposed virtual monitoring system is based on open architecture. Open architecture designs, have long been the choice for many industrial and commercial measurement systems [4]. The advantages of adopting an open architecture measurement platform span both hardware and software, providing the engineer with a wide range of choices not available to those locked into proprietary designs. An open hardware approach guarantees that a well defined set of signal and interface characteristics have been adopted, and that multiple vendors have to provide support and product development

As measuring device of the designed virtual system, a modular multifunction DAQ is suggested. The multifunctional DAQ boards perform a variety of tasks, including analogue measurements and generation, digital measurements, and timing I/O. Because the pressure sensors output voltage swing is 0 volt to 5 volt the analogue inputs of selected DAQ board must cover this voltage range. Using well-designed software drivers for modular DAQ, the engineers can quickly access functions during concurrent operation.

3.3. Design of system's software

The role of software in virtual instrumentation cannot be overstated. Software converts the raw bit stream from hardware into a useful measurement. Because of the wide variety of requirements in liquid level measurement, it is difficult to find turnkey software that utilizes the hardware components, specialized algorithms, and unique displays that the application requires. The alternative to turnkey software is application development software, or programming.

With the graphical programming approach, the users have the opportunity to focus on designing and optimizing the algorithm while the other implementation details are abstracted away providing a much shorter time to first prototype.

In this paper the use of most popular and complete graphical application development environments, such as LabVIEW is proposed. LabVIEW offers the performance and flexibility of a programming language, as well as high-level functionality and configuration utilities designed specifically for measurement and automation applications.

A well-developed virtual instrumentation system considers multiple layers of software, including instrumental drivers, application development, and results publishing and management. Every layer of this software architecture should be considered.

The bottom layer, instrumental drivers, is one of the most important elements of a virtual instrumentation system. This layer provides the connectivity between the development software and the hardware for measurement and control.

The main benefit of LabVIEW over other development environments is the extensive support for accessing instrumentation hardware. Drivers and abstraction layers for many different types of instruments and buses are included or available. With LabVIEW, it is easy to design custom virtual instruments by creating a graphical user interface on the computer screen through which the user can control selected hardware, reconfigure measurement node for acquiring various measurement data, easy implement calibration techniques, analyze acquired data and display and publish the results.

In addition, LabVIEW have object-oriented and component oriented capabilities. This open architecture approach, which lends itself to true component-based development, provides more flexibility to the user when changing requirements or architectures, or when moving from an older technology to a newer one.

4. Experimental results

In order to demonstrate usability of the presented approach a virtual system for liquid level and density measurement is developed. The system is designed to measure level in tanks up to 10 m in height with 10 mm resolution.

The block diagram of developed system is shown in figure 2. For liquid level measurement, the Freescale's MPX5100DP integrated pressure sensor is selected. It is signal conditioned and has temperature compensation and calibration circuitry on the chip. To obtain liquid density the MPXV5004DP from the same family is chosen [5].

As sensing elements for temperature measurement type K hermetically sealed tip thermocouple is provided.

In order to measure voltages generated by sensors the National Instruments' multifunctional DAQ USB-6009 is used as measuring part of the virtual system reported here. This is new generation of portable low-cost modular DAQ, controlled by computer via USB [9]. The NI USB-6009 provides connection to eight analogue input (AI) channels. The physical and electrical connection between integrated sensors, thermocouple and DAQ is shown in figure 2. Analogue input channels are configured for differential measurements.

With these 14 bits resolution DAQ, the noise that is inherent to piezoresistive sensors becomes a design consideration. For that reason, the sensor's output is filtered with an appropriate capacitor. Based on enormous capabilities of LabVIEW for data manipulations in this paper additional method for noise rejection is suggested. Method computes the harmonic mean from array of thousand measured values and displays the result. With this approach a considerable noise rejection is achieved that significant increase measurement accuracy.

In order to reject variation in voltage supply in this development is proposed ratiometric method to obtain pressure values from sensors. From equation (5) follows that with changes of V_S the output voltage V_{DP} will changes also without actual pressure variation. As can be seen in the figure 2 besides the voltages from the sensors V_{DP1} and V_{DP2} the supply voltage V_S is measure also (using analog input AI2). Therefore, equation (5) becomes:

$$\Delta P = \frac{\frac{V_{DP}}{V_S} - N}{S} . \qquad (6)$$

Equation (6) is ratiometric because the voltage ratio V_{DP}/V_S will be constant regardless voltage supply variations. Additionally, this approach makes the system less sensitive to external interferences.

The front panel of developed virtual system for liquid level monitoring is shown in figure 3.

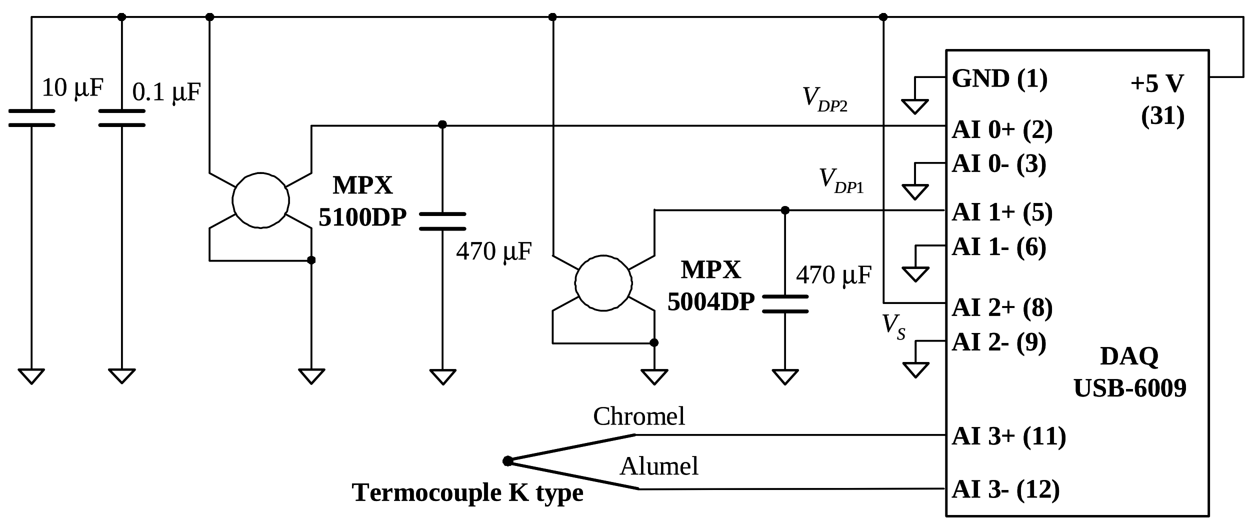

Figure 2. The block diagram of developed system for liquid measurement

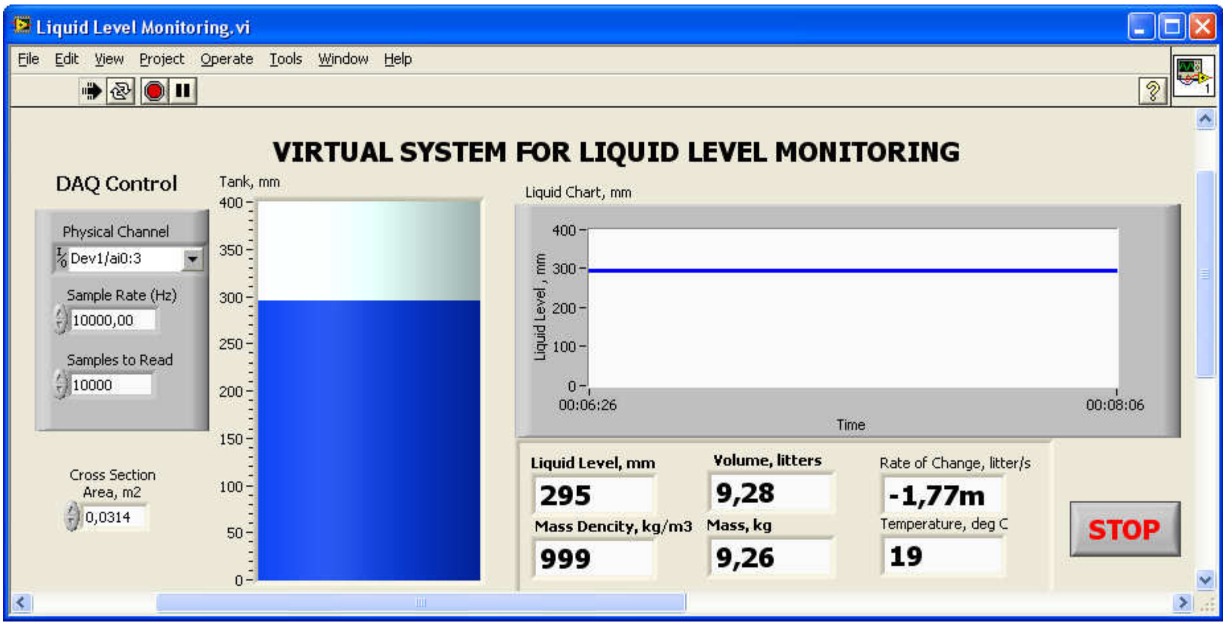

Figure 3. The front panel of developed virtual system for liquid level monitoring

The presented software design goals included user configuration of DAQ parameters as is shown in left part on the figure. To further increase the challenge of this application, it is necessary the instrument condition and run progress to be visible and understandable at a glance and the user interface to be simple and logical yet attractive and intuitive in presentation.

To illustrate efficiency of the developed system a laboratory experiment with vessel filled with fresh water 30 cm in height is done. As can be seen from digital indicators located in bottom of the figure 3 an excellent accuracy for measured water density and level is achieved.

The disadvantage of presented virtual system is the necessity of wires that connect sensors to data acquisition board. This is especially inconvenient when liquid level in large tanks must be measured. To improve this disadvantage design and development of a wireless virtual monitoring system is intended as further research.

5. Conclusion

In this work, implementation of virtual measurement technology for continuous liquid level and density measurement has been presented. An approach has been introduced for the accurate measurements of the density of liquids by a monolithic differential pressure sensor. To illustrate usability of the presented approach virtual system based on monolithic differential pressure sensors, multifunction DAQ and LabVIEW has been developed. This system design concept may be used to develop a various low cost liquid level measurement and monitoring systems with measurement range from 0.4 m up to 70 m.

References

1. Boyes, W.: *Instrumentation reference book*. Butterworth-Heinemann, ISBN 0-7506-7123-8, USA, 2003
2. William, D.: *Fundamentals of Industrial Instrumentation and Process Control*. McGraw-Hill, ISBN 0-07-145735-6, USA, 2005
3. Hamelain, J.: *Liquid Level Control Using a Pressure Sensor*. Available at: http://www.freescale.com/files/sensors/doc/app_note/AN1516.pdf. Accessed: 2005-05
4. Bishop, R.: *Mechatronic System Control, Logic and Data Acquisition*. CRC Press, ISBN 978-0-8493-9260-3, USA, 2008
5. Freescale Semiconductor: *Sensors Device Data Reference Manual*. Available at: http://www.freescale.com/files/sensors/ doc/data_lib/DL200.pdf. Accessed: 2007-01
6. http://www.directindustry.com/industrial-manufacturer/pressure transmitter-64758.html. Accessed: 2008-02-17
7. Clifford, M.: *Water Level Monitoring*. Available at: http://www.freescale.com/files/sensors/doc/app_note/AN1950.pdf. Accessed: 2006-11
8. Nikolov, G., Nikolova, B., Marinov, M.: *Hazardous Gas Monitoring Using VI Server*. ELECTRONICS'2007, book 3, p. 93-98, ISBN 1313-1842, Sozopol, September 2007, TU, Sofia, Bulgaria
9. National Instruments: *USB-6008/6009 User Guide and Specifications*. Available at: http://www.ni.com/pdf/manuals/371728b.pdf. Accessed: 2006-04

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