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Wireless sensor network-enabled intravenous infusion monitoring

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Abstract: Considering that intravenous in blood infusion, usually applied without a proper control of the progress and velocity under unreliable manual monitoring practice, is the most popular and frequent clinical activity throughout the world, which can potentially endanger a patient's life, leads to a huge burden as patients, relatives and nursing staff can cause serious cases of medical negligence. In order to resolve this problem and provide a networkable solution the authors propose a novel radio frequency identification-based wireless sensor networkable intravenous infusion monitoring system. The proposed system is a wireless sensor system based on taking a fork-type light barrier as a sensor, a micro-control unit (MCU) as a ZigBee-based radio frequency device. The system's performance is evaluated through some laboratory experiments using tuning algorithm to demonstrate that the results show the required accuracy of the system to meet practical needs.

1 Introduction

Intravenous infusion is important and part of common practice in clinical treatments [1, 2]. Medical negligence during intravenous infusion could cause various kinds of serious medical complications. In 2009, for example, an 18-month-old child died because a blood-reflux accident occurred during the intravenous infusion in the hospital of Liangchen, Wuxi, Jiangsu, China. Without an access or any information on the progress and velocity of the intravenous infusion this is becoming a key risk factor leading to similar medical accidents.

To solve this problem there have been several specialised and complicated medical instruments. For example, an infusion pump [3] is able to control the infusion velocity strictly and cut down the infusion tube at the end of intravenous infusion in case of blood reflux. However, these specialised medical instruments cannot be considered practical or ideal because of many drawbacks and disadvantages including: (i) their high price and complexity make them difficult to be used for large-scale applications; (ii) their requirement for professional cleaning for reuse makes them discommodious to use when compared with disposable infusion tubes; (iii) no networking capability limits their functionality and makes them inconvenient to be integrated into the hospital information system (HIS).

In order to overcome the practical drawbacks of the existing instrumentation systems, this paper presents a new design and implementation approach for a novel wireless sensor network (WSN)-enabled intravenous infusion monitoring system. Where, with WSN technology [4, 5], using smart sensors and radio-frequency (RF) communication technologies, we can facilitate new features such as real-time access, perception, acquisition and transmission of data. This system enjoys the following characteristics: convenient for reuse, as it adopts non-contact droplet monitoring method; accurate and reliable, as it takes multiple protection measures; scalable, as it is able to integrate with HIS in providing extensive reliable information via the web service; low cost, which facilitates global-scale market under the large-scale integrated technology.

This paper is organised as follows. In Section 2, we provide an overview of the challenges associated with monitoring the progress and velocity of intravenous infusion. Section 3 introduces the principle of the approach we adopted. Then, in Section 4 we illustrate the architecture of the system. In order to appreciate sensor nodes specific real-time monitoring features of the system, in Section 5 we detail the design of monitoring sensors. In Section 6, we look into the software part of the intravenous infusion monitoring, which is divided into two parts: The embedded software in the sensor nodes and the monitoring system in the host computer. We then explore the protection mechanism designed for system reliability in Section 7 and then show our experimental results in Section 8 before concluding the paper in Section 9.

2 Goals and challenges

We identify the following challenges in our solution:

Provide intravenous infusion statistics: The intravenous infusion system should be able to perceive every patient's infusion progress and provide statistics on the host computer to nurses.

Assist nurses: At the end of intravenous infusion or when the velocity is beyond the threshold in the progress, the intravenous infusion monitoring system should be able to notify the nurses.

Low-cost sensors: The system should operate with sensors that are typically used in monitoring infusion progress and in large-scale applications. This constraint rules out the possibility of using expensive specialised sensors such as laser scanners.

Fault tolerance: There are various exceptions in practical scenarios (e.g. message losses or omissions in sensing caused by patients' movement). The system should be able to recognise exceptions according to the multiple protection mechanism.

3 Principle

In this paper, the system perceives the progress and velocity of intravenous infusion through droplets monitoring. Hydromechanics theory shows that under the condition of approximately static 'Nkosi steady state' [6], when the velocity is low enough, the weight of a droplet is only related to the surface tension. However, there are many factors that influence the surface tension, including concentration and property of liquid, size and shape of the dropper section, temperature, humidity etc. In practical applications, under the condition of given infusion tube type and little change in temperature and humidity, the main factors that affect droplet weight are medicine species and droplet velocities [7, 8]. We then generate an empirical formula through analysing experimental statistics of droplet quantity contained in per millilitre under different medicine species and droplet velocities. Based on the formula, we present our enhanced tuning algorithm [9], which improves the precision of automatic monitoring. In the experimental analysis section of this paper, we then analyse the effects of this on the monitoring precision for different medical samples and droplet velocities in further detail.

4 Architecture

A typical scenario for using this system is shown in Fig. 1. The monitoring sensor of intravenous infusion adopts Murphy's dropper [10] for a disposable infusion tube. As shown in the 'Sensor Node' of Fig. 1, Murphy's dropper is embedded in the fork-type light barrier where the sensor node is responsible for droplet signal detection, waveform adjusting, data transmission, light-and-sound alarm and so on. The sink node is responsible for collecting data from monitoring sensor nodes and then transmitting them to the host computer deployed in the nursing station through a serial port. The monitoring software installed in the host computer is in charge of the progress monitoring, display and alarm. The monitoring software also provides integrated interfaces to HIS through windows communication foundation (WCF) technology.

The structure of an intravenous infusion monitoring sensor is shown in Fig. 2. The structure of a sink node is similar to that of a monitoring sensor node only but the latter has no sensor component and waveform adjusting circuit. The sensor node mainly consists of three functional modules: a droplet signal monitoring module based on a fork-type light barrier along with its waveform adjusting circuit, an micro-control unit (MCU) module based on an ATMEGA128L controller and an RF communication module based on a CC2420 chip [11, 12].

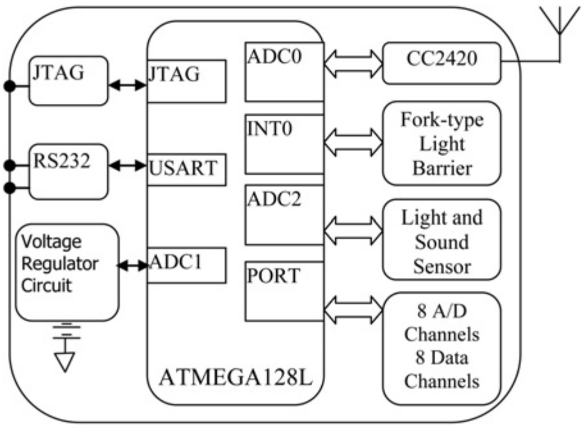

Fig. 2 *Structure of the sensor node*

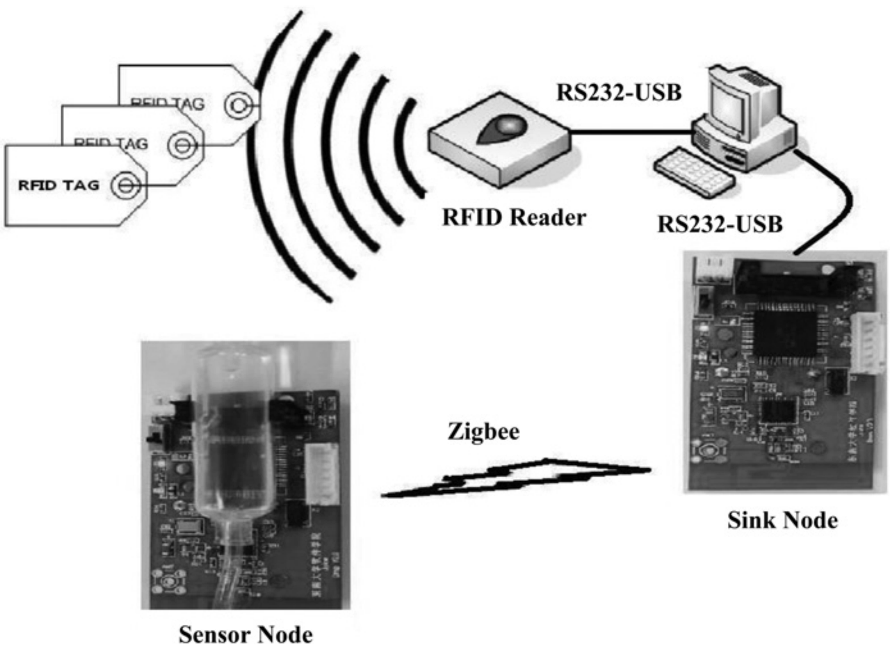

Fig. 1 *Typical deployment scenario*

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5 Design of monitoring sensor node

5.1 Design principle and scheme of intravenous infusion monitoring node

The target application scenario of the system is indoor medical environment. There may be interferences from other instruments working on the same frequency bands and significant signal attenuations caused by various obstacles, where instant recharging and infrastructure of power supply can reduce the constraints on energy consumption. Thus, the principal design target of the sensor nodes is to provide reliable communication and relatively strong performance. In our typical model we have used an ATMEGA128L and a CC2420 for our networking scenario along with a fork-type light barrier, an easy-to-deploy sensor, to design the intravenous infusion sensor node.

5.2 Selection of sensor components

Our investigation indicates that the available sensors in the market, which can monitor droplets or liquid level, can be divided into several groups including ultrasonic sensors, laser sensors, fork-type light separate barriers and classic fork-type light barriers. Taking several practical factors into account including precision, anti-interference, cost, power consumption, distance, size and deployment, as shown in Table 1, we have chosen classic fork-type light barrier for our experimental system.

The classic fork-type light barrier with a 1.5-cm-diameter slot adopted in the system provides prominent advantages of low cost, low power consumption and small size. Furthermore, the 1.5×5 cm Murphy's dropper of a disposable infusion tube can be exactly and easily embedded into the 1.5-cm-diameter slot on a classic fork-type light barrier.

5.3 Design of the monitoring circuit

The circuit diagram of the sensor is shown in Fig. 3. When there is a droplet going through a fork-type light barrier, the receiver of the fork-type light barrier will generate a pulse signal. The signal after the comparison is amplified by LM393. In this experiment, we discovered that owing to lack of stability analysing the outputs of a fork-type light barrier is rather difficult. Using the outputs directly will lead to omission in sensing and conflicts in interrupt handling programs. Thus, we have used a NE555CN circuit as a mono-stable to generate a pulse signal with a certain interval so as to adjust the waveform to the same duty cycle, and then our experimental results have been improved significantly. The signal is then sent to create an interrupt in the microcontroller circuit. Meanwhile, we place an LED on the signal output interface to observe the working state of the fork-type light barrier.

5.4 Design of the MCU module and RF communication module

The MCU module and RF communication module of the sensor node are the same as those of the sink node. The ATMEGA128L is adopted in the MCU module. Designed into RISC architecture, this chip has a high performance with low power consumption. The program of the sensor node can be written into a 128k programmable flash through serial peripheral interface (SPI). The 128k flash ensures the storage of objective codes. Furthermore, the ATMEGA128L shows good performance up to 16MIPS of throughput at 16 MHz and can provide strong support for networking. On the other hand, the ATMEGA128L comes with two programmable serial ports which make the sink node communicable with the host computer. This chip has a programmable watchdog timer with an On-chip Oscillator, and so it is able to recover automatically after exception. These features guarantee the reliability of the system.

Considering that proper design of the RF communication module is crucial for reliable communication, a suitable selection of the RF circuit and its correct design may directly influence the distance of communication. Therefore selection of CC2420 as the RF chip with SmartRF 03 [13] technology ensures a stable performance for RF communication.

Table 1 Comparison of droplet monitoring sensors

Type	Precision	Anti-interference	Cost	Power	Distance	Size	Deployment
ultra-sound sensor	high	strong	high	high	middle	large	inconvenient
laser sensor	high	strong	high	high	far	middle	inconvenient
fork-type light separate barrier	middle	weak	low	low	middle	small	inconvenient
classic fork-type light barrier	middle	middle	low	low	near	small	convenient

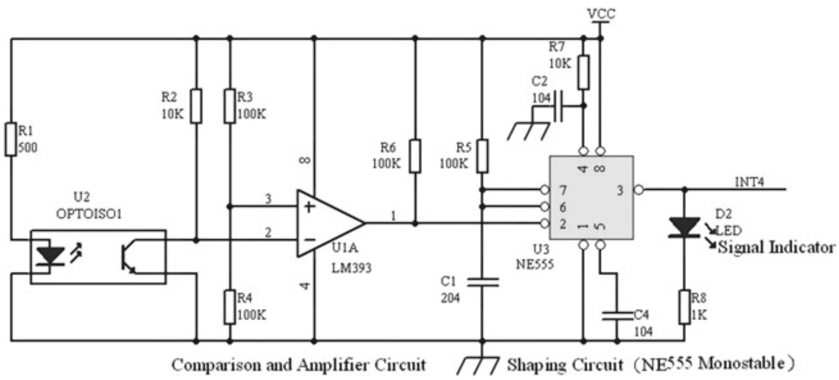

Fig. 3 *Schematic of the sensor component*

Moreover, the CC2420 conforms to the IEEE802.15.4 standard and also exceeds the standard for selectivity and sensitivity, which ensures the effectiveness and reliability of short-range communication. The 250 kbps effective bandwidth provided by this chip ensures network extensibility and meets the needs of intravenous infusion monitoring applications. The CC2420 RF interface supports 16 channels of all the 26 channels in a 2.4 GHz frequency band. Moreover, channel conflicts are inevitable because it works under 2.4 GHz frequency band, free to all applications. When a sharp decline in throughput or serious message conflicts occur in the process of information transmission, the multi-channel mechanism of the CC2420 will change the channel to improve throughput and guarantee reliability. RF communication can be easily realised by a CC2420 accompanied with few external components. The principle of the external circuit of a CC2420 is shown in Fig. 4. The RF circuit is sensitive to the interference between components and so a double-layer PCB board is chosen in the sensor node and some via holes are placed in the open region to connect ground (GND) on both sides. Moreover, the bottom of the CC2420 is also connected to GND through some holes. In order to improve the performance of the RF part for an extended communication range, decoupling the capacitors is proposed. The PCB inner antenna is adopted as the RF antenna of the sensor node so that the weight of the sensor node is reduced. Through experiments, we find that the communication range with a PCB inner antenna (20–30 m indoors) meets the needs of virtually all intravenous infusion systems in the hospital.

6 Intravenous infusion monitoring system

6.1 Software of sensor nodes

The sensor software runs on the MCU of sensor nodes and sink nodes. It is responsible for node control, interrupts handling, wireless communication, serial port communication, alarm on exceptional cases, fault recovery etc. However, developing the software independently can result in many disadvantages, such as large amounts of workload and poor portability. Thus we have adopted a system-level development based on TinyOS, component-based operating system developed by UC Berkeley, to develop and implement the sensor software. In TinyOS, we just focus on the design and implementation of business logic, because other factors such as task-switching, interrupt handling, serial port communication and ZigBee protocol stack are already provided as generic functions by the components.

It is an optimal design pattern to separate the design of hardware-dependent codes from that of hardware-independent codes on a specific sensor hardware platform. Thus in order to facilitate application development in the future, we add a middle layer worked as a sensor hardware-dependent logic component, as shown specifically in Fig. 5. The 'InterruptC' component is an interrupt handling model which defines the interface of interrupt and reserves the interrupt handling realisation; the 'GenericComm' component is a relatively complex logic model which combines interfaces provided by TinyOS to realise Zigbee network communication and serial port communication; the 'CC2420RadioC' is an RF

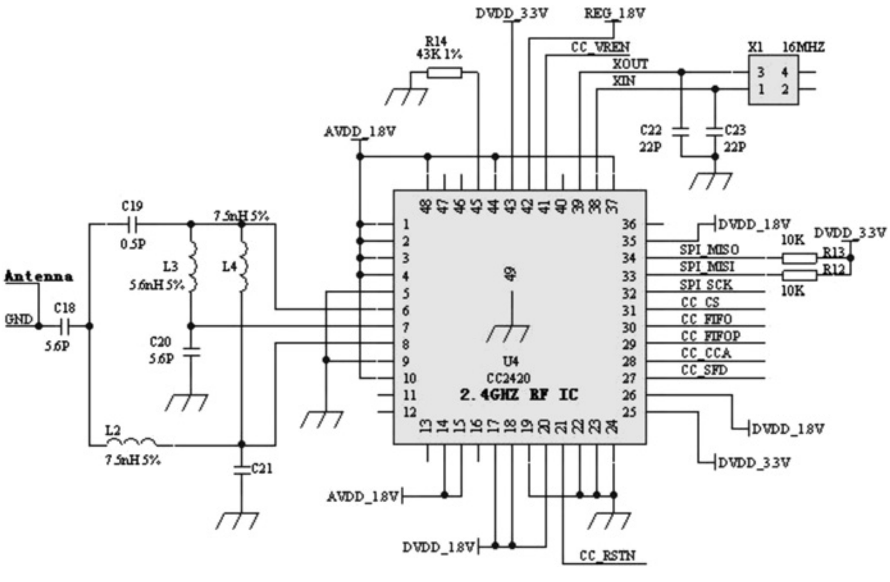

Fig. 4 *Schematic of the RF communication component*

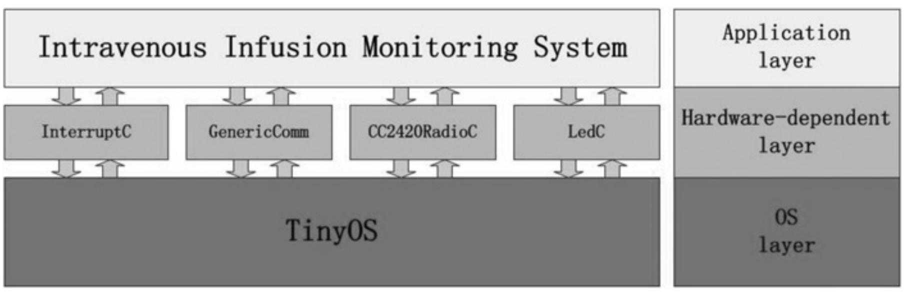

Fig. 5 *Software structure in the sensor node*

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component related with power control, energy conservation, communicational distance etc.; the 'LedC' component is used for signal indicative control.

The hardware-dependent layer shields the definitions of the interfaces in TinyOS, which has the following benefits: (i) it makes application development based on this hardware platform easy; (ii) it makes the framework of upper-layer application clear; and (iii) it makes code style humanistic. Moreover, TinyOS has many advantages such as tiny object codes, high efficiency, shielding of hardware differences etc. Thus, it suits WSN applications with restricted computational power, memory and energy.

In order to decrease power consumption and to save bandwidth we need to reduce sensor node's software complexity. This would help the sensor node application-layer software to be responsible only for the most fundamental required functions of precise and reliable intravenous infusion monitoring. Once an interrupt is triggered by a droplet signal, the software changes the droplet counter and the droplet interval timer. The droplet velocity is calculated according to the interval of the latest N droplets (the general value of N is 5). If the droplet velocity exceeds the initial given scope of velocity, a light-and-sound signal and an emergency-alarm message will be sent out. The droplet count value and droplet velocity are sent to the host computer software periodically in the form of a synchronous message. The sending frequency of messages changes according to the intravenous infusion progress: the frequency is low at the beginning, and at the end of intravenous infusion, every droplet will trigger a synchronous message. Working in this way not only ensures precision but also saves bandwidth and reduces power consumption. In order to guarantee the reliability of the system, the sink node and the host computer transmit heartbeat messages mutually. If any part of the system cannot receive other's heartbeat message within expected time, there will be a light-and-sound alarm immediately.

6.2 Radio frequency identification software design

In order to integrate the system with HIS to provide humanistic service for patients, the radio frequency identification (RFID) technology is adopted in the system to import patients' information, as shown in Fig. 6. The EM4904_RFID_V1.0 module produced by Hanback Company is used as RFID card reader, the most widely used type (13.56 MHz). Using installed antenna, the card reader communicates with RFID tags around through the binary phase shift keying (BPSK) modulation scheme. Our system uses passive RFID tags. When entering the electromagnetism field of the reader, the tag obtains energy from capacitors charged through an inner antenna. After obtaining enough energy, the tag transfers data to the card reader by changing electromagnetism around the card reader. In this example, the tag has saved a unique id. The unique id is assigned by HIS so that the intravenous infusion monitoring system is able to obtain patients' information. The software based on TinyOS calls the 'RFID_Control' interface provided by Hanback Company to read the unique id saved in the RFID tag.

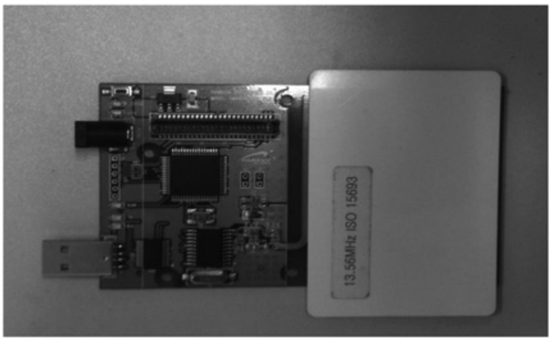

Fig. 6 *RFID card reader*

6.3 Software of the host computer

The host computer software runs on a computer deployed in the nursing station. It is responsible for providing human – machine interface, automatic detection of the intravenous infusion progress and velocity, and alarm functions. It also provides an interface to HIS. The software takes droplet quantity per millilitre of different medicines at different droplet velocities as tuning parameters to estimate the progress and velocity of intravenous infusion. There is some information, such as patient's identity, medicine species, total volume and velocity scope, which can be obtained from HIS. The graphic interface of intravenous infusion monitoring system is shown in Fig. 7.

We mainly use the Model View Present (MVP) design pattern to develop the host computer software. The design pattern, as shown in Fig. 8, realises the interaction between the 'Model' layer and the 'View' layer through the 'Presenter' layer in order to separate interface design from business logic. The 'SerialAssistant' parses the message received from the sink node and updates the 'MandrugModel' and then it transfers these data to the 'MonitoringView' through the 'MonitoringPresenter'. In addition, the host computer software combines thoughts such as factory model and single model together. The combination makes the system possess high cohesion and low coupling, which facilitates the maintenance and redevelopment.

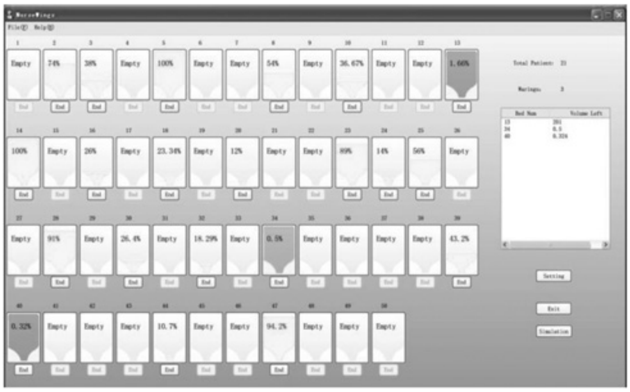

Fig. 7 *Graphic interface of the intravenous infusion monitoring system*

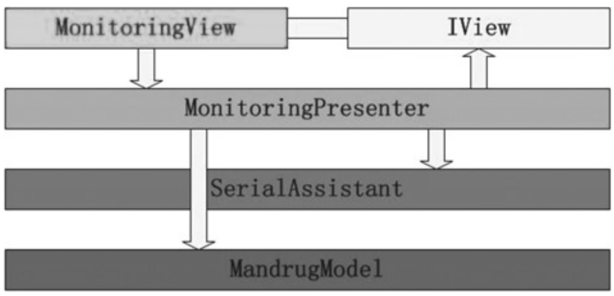

Fig. 8 *MVP design pattern in the system*

The graphic interface, which is worked over and designed based on aesthetics, is decent and graceful. The host computer software is supported by Microsoft mainstream technology products. Interface is designed by windows presentation foundation technology, graphic rendering library in Windows7. Database is supported by SQL Server2005 which has stable performance. WCF technology makes the system easy for third-party members to carry on further development.

7 Protection mechanisms for system reliability

7.1 Precision guarantee

In order to guarantee the availability of the system in the hospital, we have performed many experiments on the precision and reliability.

First, we analyse the droplet quantity per millilitre influenced by different medicine species. We fix related parameters such as the type of infusion tube and droplet velocity and then test the droplet quantity of different medicine species per millilitre repeatedly at room temperature. We find that droplet quantity per millilitre is mainly influenced by liquid viscosity. The results are shown in Table 2.

Table 2 shows that the droplet quantity of different medicine species per millilitre is different, and so the system takes medicine species into consideration in the tuning algorithm.

Second, we analyse the droplet quantity per millilitre influenced by different droplet velocities. The results are shown in Table 3.

Table 3 shows the relationship between droplet velocity and droplet quantity per millilitre. In common, high velocity leads to a bigger droplet so that droplet quantity is less per millilitre, the result is consistent with Poiseuille equation [14] $Q = (p1 - p2)\ R(Q$ represents for flow load, $p1 - p2$ represents for pressure difference between the ends of the infusion tube, R is the flow resistance). The automatic detection module of the host computer software sets tuning parameters automatically according to real-time droplet velocity to guarantee precision.

Table 2 Droplet quantity per millilitre influenced by different medicine species

Medicine species	Droplet quantity per millilitre
5% glucose	20
10% glucose	19.5
physiological saline	20
dextran-40	19

Table 3 Droplet quantity per millilitre influenced by different droplet velocities

Droplet Velocities, drops/min	5% Glucose, drops/ml	10% Glucose, drops/ml	Physiological saline, drops/ml	Dextran-40, drops/ml
10	21	20.5	21	20
40	20	19.5	20	19
70	19	18.5	19	18
100	18	17.5	18	17

7.2 External exceptions

There are various exceptions in practical scenarios such as power outage of a sensor node, breakdown of the host computer software, message loss caused by radio interference, omission in sensing caused by patient's movement and invalidation of the fork-type light barrier when it is interfered by strong outdoor light. In order to handle each situation mentioned above, we take measures in the design of the software and hardware.

The battery volume of a sensor node is limited. Apart from some necessary controls in energy saving, we also take some measures to handle the exceptions caused by power outage. The system will consider the sensor node out of power if heartbeat message is not received by the host computer. In the meantime, the host computer software alarms a specific node exception and enters into abnormal nodes sync state. In the sync state, the host computer software calculates average droplet velocity in current minute according to previous droplet velocities. After the sensor node has been charged with new battery and recovers to normal performance, the host computer software turns from sync state into tuning state. In tuning state, the host computer software contrasts the calculated velocity with current velocity in order to make the calculated velocity more precise. The switch of states in the host computer is shown in Fig. 9.

As shown above, the host computer software plays a crucial role in the whole intravenous infusion monitoring system. When the host computer software crashes, how does the system deal with it? First of all, the system will consider a crash of the host computer if the heartbeat message is not received by the sink node. Meanwhile, the sink node warns nurses to restart the host computer. After restarting, the host computer software scans log files to import patients' information into the system. Since each message sent from a sensor node has been labelled with a sequence number, the remaining drop volume is easy to restore to a practical volume in the host computer software.

Radio interference may cause message loss and then the host computer software will receive intermittent messages which should be continuous in perfect network condition. However, the message sent by each sensor node has been labelled with a sequence number, and so the remaining drop volume is easy to restore to a practical volume in the host computer software.

Patients may need to be moved during the process of intravenous infusion, which may lead to omission in sensing. The system is able to consider omission of data when caused by a sudden change in the average reading of droplet velocity per minute and then enters into the sync state.

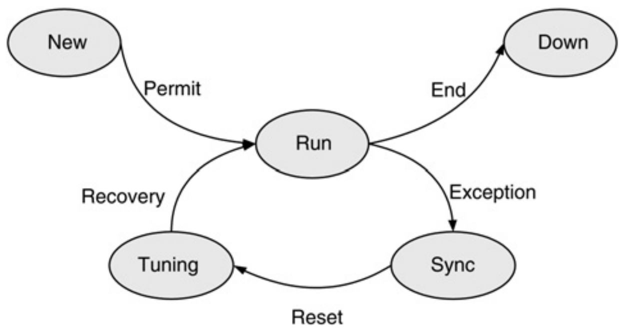

Fig. 9 *Switch of states in the host computer software*

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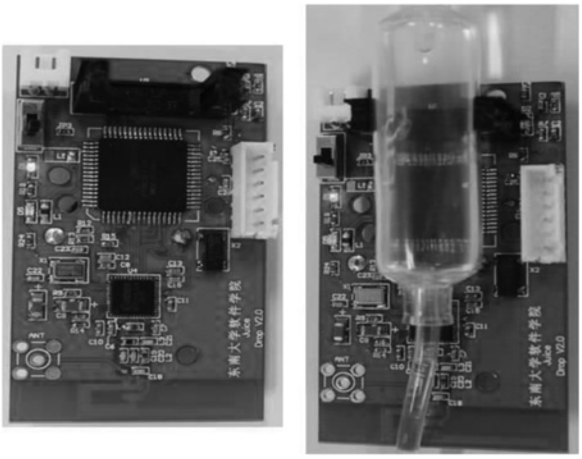

Fig. 10 *Intravenous infusion monitoring sensors*

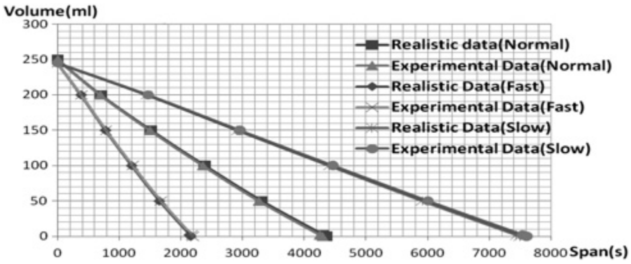

Fig. 11 *Experimental statistics of 10% glucose*

In the experiment, we find that the fork-type light barrier is light sensitive and it loses effectiveness when it is interfered by strong outdoor light. Thus, in the deployment of the sensor node, a block of sun visor on each side of the sensor needs to be placed to avoid the interference caused by strong outdoor light.

8 Experimental results

The intravenous infusion monitoring sensors we produced are shown in Fig. 10.

Finally, we test the precision of the whole system. At room temperature with 10% glucose as an example, we compare the progress in the monitoring system with that in reality according to 20 sets of experimental raw data in different droplet velocities. The experimental statistics of 10% glucose is shown in Fig. 11 where the vertical axis stands for remaining drop volume (in ml) whereas the horizontal axis stands for intravenous infusion span (in s). Using tuning algorithm in the experiment, we find that the remaining drop volume in the system is quite close to the practical remaining drop volume in the process of intravenous infusion [several points in the figure (e.g. 200, 150, 100, 50 and 0 ml) are the milestones in which we record and compare the data]. The accuracy meets the practical needs.

9 Conclusion

This paper illustrates a family of intravenous infusion monitoring systems based on a fork-type light barrier incorporated with the ZigBee protocol. We analyse the reliability of the system and provide massive experimental statistical results to show that the monitoring system is capable of providing all required functions of networkable system, monitoring the progress and velocity of intravenous infusion with high precision and reliability. Moreover, the system comes with prominent practical advantages of low cost, low power consumption, small size, good scalability, convenient deployment, flexible use and many more for most clinical and non-clinical uses.

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11 References

1 Dudde, R., Vering, T., Piechotta, G., Hintsche, R.: 'Computer-aided continuous drug infusion: setup and test of a mobile closed-loop system for the continuous automated infusion of insulin', *IEEE Trans. Inf. Technol. Biomed.*, 2006, **10**, (2), pp. 395–402

2 Simon, N.: 'Impact of infusion method on amikacin serum levels in humans', *Pulmonary Pharmacol. Therapeut.*, 2010, **23**, (4), pp. 324–326

3 Robert, S., Wilcox, S.J.: 'The link between intravenous multiple pump flow errors and infusion system mechanical compliance Murphy', *Anesth. Analg.*, 2010, **110**, (5), pp. 1297–1302

4 Wheeler, A.: 'Commercial applications of wireless sensor networks using ZigBee', *IEEE Commun. Mag.*, 2007, **45**, (4), pp. 70–77

5 Ni, S.-Y., Tseng, Y.-C., Chen, Y.-S., Sheu, J.-P.: 'The broadcast storm problem in a mobile ad hoc network'. Proc. Int. ACM/IEEE Int. Conf. on Mobile Computing and Networking, Seattle, Washington, USA, August 1999, pp. 151–162

6 Batchelor, G.K.: 'The effect of homogeneous turbulence on material lines and surfaces', *Proc. R. Soc. Lond.*, 1952, **213**, (A), pp. 349–366

7 Ziser, M., Feezor, M., Skolaut, M.W.: 'Regulating intravenous fluid flow: controller versus clamps', *Am. J. Hosp. Pharm.*, 1979, **36**, (8), pp. 1090–1094

8 Weiss, M., Hug, M.I., Neff, T., Fischer, J.: 'Syringe size and flow rate affect delivery from syringe pumps', *Can. J. Anaesth.*, 2000, **47**, (10), pp. 1031–1035

9 Berg, M.d., Schwarzkopf, O., Kreveld, M.V., Overmars, M.: 'Computational geometry: algorithms and applications' (Springer, 2000, 2nd edn.)

10 Guo, H., Liang, A., Li, L., Guan, X., Bian, H.: 'Test study on fluid height of Murphy's dropper and loss of transfusing whole blood erythrocyte', *J. Pract. Nurs.*, 1998, **14**, (5), p. 255

11 http://www.zigbee.org, accessed December 2009

12 Chipcon, A.S.: 'CC2420 2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver'. Data Sheet, Rev.1.4, 2006

13 http://focus.ti.com.cn/cn/lit/ug/swru070k/swru070k.pdf, accessed December 2009

14 Goldstein, S.: 'Modern developments in fluid dynamics: an account of theory and experiment relating to boundary layers, turbulent motion and wakes' (Dover Press, 1965)