Are Today’s Embedded Systems Capable of Facilitating Home Hemodialysis?

Francis Pellicano
Tagliatela College of Engineering
University of New Haven
West Haven, Connecticut
fpellicano@newhaven.edu

***Abstract*— Kidney disease is a leading cause of death in the United States. The primary function of the kidneys is to cleanse blood of toxins. As kidney function starts to deteriorate and fail, these toxins cause other health issues leading to a reduced quality of life and higher morbidity. Hemodialysis is a procedure which connects patients to a machine that simulates kidney function to filter blood and prolong patient life. A minimum effective dosage requires patients to travel to a dialysis center 3 to 4 times a week for 4 hours per session. Centralized treatment at a dialysis center devalues patient time and convenience and aims for minimum treatment times to maximize patient throughput. Although longer or more frequent sessions would improve patient health and increase life expectancy, travelling to a medical center multiple times per week for many hours in a day is strenuous and decreases patient quality of life. Development of a home hemodialysis machine would improve patient quality of life by reducing scheduling, providing a comfortable and familiar environment, as well as facilitating longer treatment. Due to the technical complexity of hemodialysis machines, developing a home solution requires a deep understanding of embedded systems and their role in hemodialysis. Progress in the field of embedded hardware and software have revolutionized many industries, including the medical field. As such, today’s embedded systems are capable of facilitating home hemodialysis, however there are technical challenges which must be considered.**

Keywords—Embedded Systems, Hemodialysis, Kidney Disease, Home Dialysis

I. Motivation

Modern technology is redefining the healthcare industry as embedded systems rapidly advance in capability. One such benefactor of the advancement of embedded systems is dialysis technology used to aid patients with chronic kidney disease (CKD). Early dialysis machines, first becoming mainstream in 1968, used simple technology for blood filtration which was quite laborious in application. As mentioned by C. Graansma, the 21st century saw dialysis machines experience significant technological improvements in operation, reliability, and accuracy [1]. Despite these advancements, kidney disease continues to be a leading underlying cause of death in the United States, ranking 10th in 2021 [2]. According to the Center for Disease Control (CDC), more than 1 in 7 US adults are estimated to have CKD, with advanced stages requiring dialysis treatment or kidney transplant [3]. CKD can cause health problems such as nausea, cardiovascular disease, lowered immune system, and death. The goal of dialysis treatment is to simulate kidney functionality by removing waste and extra fluids from the blood. A 2021 study of dialysis patients found a considerable number of CKD patients suffered from treatment-related burden and a deterioration in quality of life (QoL) [4]. The study found that lifestyle and administrative changes, including scheduling and traveling to treatment appointments, were the second and third highest reported burdens impacting QoL. Outcomes of healthcare include monitoring or improving patient conditions when in poor health and increasing life span and quality. Centralized healthcare at a dialysis center utilizes a central hub where all ailing patients travel to, however this does not take into consideration patient logistics or motivation to travel to such location. A method to improve QoL and mitigate these challenges would be to treat patients in their own home instead of requiring appointments or travel to a dialysis center multiple times in a week. One company, NxStage, began development of a home hemodialysis machine in 2005. In 2017, they became the first and only company to release a hemodialysis machine approved by the Food and Drug Administration (FDA) for independent home use. Despite expectations of 15% utilization by hemodialysis patients within 4 years, their machine was only utilized by 1% of patients in that timeframe and failed to become a viable option for home treatment [5]. NxStage felt limitations in technology and usability are the primary reasons their machine was not successful. A 2020 study published in Kidney Medicine Journal found certain populations had better QoL when treated with home dialysis instead of at a dialysis center [6]. Although the study concluded that the data came with limitations in patient population, the authors felt an at-home solution would reduce the lifestyle and administrative burdens placed on a patient. Additionally, home dialysis makes availability for more frequent sessions possible. D. Silverstein found that there are clear advantages to increased frequency of dialysis treatments [7]. Observational studies correlated reduced risk of cardiovascular disease, health related QoL, and improved cognition with increased frequency of treatments. Graansma concluded that a home solution would be the future of dialysis, however there are technical obstacles preventing greater home dialysis utilization.

Dialysis can be sub-divided into peritoneal dialysis and hemodialysis. While hemodialysis relies on an external membrane to act as an artificial kidney [8], peritoneal dialysis utilizes the internal tissue lining of the abdomen wall to act as a natural blood filter. A catheter is permanently installed into the patient's abdomen and allows treatment to easily be performed at home [9]. Minimal training and equipment are required for patients to perform treatment. As a result, peritoneal dialysis offers greater lifestyle flexibility and lower morbidity [9]. Despite the advantages, peritoneal dialysis is significantly less common amongst CKD patients. A. Kaplan noted that 88.4% of patients begin treatment with hemodialysis, 9% with peritoneal dialysis, and 2.6% received a preemptive kidney transplant [10]. Catheter placement, availability, and patient dedication are among the reasons hemodialysis has become the preferred modality for patients. Additionally, the abdominal lining cannot be replaced and can become less effective over time [9], thus hemodialysis is also a longer-term solution. As such, manufacturers of dialysis technology have focused on hemodialysis solutions. Hemodialysis machines are a technical marvel which utilize a complex system of embedded hardware and software to accomplish the task of intravenous blood filtration. As the demand for an at-home solution rises [11], a thorough understanding of modern embedded systems is required to determine the viability of a solution which can accommodate cost effective delivery, be user-friendly, and meet the needs of patients in a home environment. The specific aims of this research are to evaluate today's embedded systems and determine if technology has advanced enough to develop a hemodialysis machine which can truly facilitate home hemodialysis.

II. Hemodialysis Application of Embedded Systems

As defined by L. De Micco, an "embedded system refers to electronic equipment with a computing core which, unlike a personal computer, is designed to meet a specific function" [12]. The general design of such system, as shown in Figure 1, utilizes one or several processors to interact with the physical world through input and output connections. Those connections are determined by the specific tasks or functions which the system is designed to solve. Complex challenges often require complex solutions, which can result in a wide variety of sensors, actuators, and occasionally human interaction.

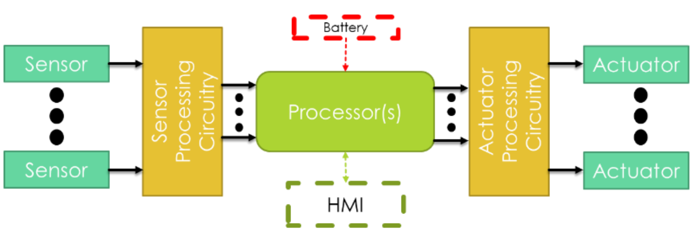

Figure 1: Simplified block diagram of an embedded system. One or several processors exert actions on the physical medium through actuators, basing their decisions on variables measured by sensors. It is common for these systems to be self-contained utilizing battery power, and, occasionally, may incorporate a human to machine interface [11].

There are numerous processing devices, typically classified as application-specific integrated circuits (ASICs), microcontroller units (MCUs), or field-programmable gate arrays (FPGAs). MCUs and FPGAs are highly customizable by a user and are capable of a wide range of general-purpose computing. ASICs, on the other hand, are built with a specific application in mind, such as modules designed explicitly for ultrasonic transducer measurement [13]. Modern silicon manufacturing techniques have given designers the ability for processors to incorporate an entire system on a chip, as these devices typically include numerous functionalities such as built-in memory and conversion modules between analog and digital signals. A wide variety of sensors and actuators exist with which these processors are designed to interface. While the processor is integral to embedded systems, the inputs and outputs to the system are the most imperative aspect. The focus of a product design is on the functionality required of those inputs and outputs.

A. *Hemodialysis System Design*

Hemodialysis machines are designed to simulate kidney function by extracting contaminated patient blood, cleansing it with a dialysate mixture while being passed through a filter, called a dialyzer, and returning purified blood to the patient [14]. Due to regulations by the FDA and standards set by the International Electrotechnical Commission (IEC), these machines incorporate numerous monitoring and alarm systems to safeguard patients from potential equipment failure during the dialysis treatment. Designers typically add sensors which do not impact the functionality of the machine but add redundancy or improve patient safety. Figure 2 shows a typical system diagram of a hemodialysis machine. Inputs to the system are purified water, concentrates for the dialysate solution, heparin, and contaminated patient blood through intravenous needles or catheter tubing. Outputs from the system are dialysate waste and purified blood which is returned to the patient. Treatment is typically performed 3 to 4 times per week over the course of 4 hours [15]. The hemodialysis system can be divided into two sections consisting of a dialysate circuit and a blood circuit, with each containing a variety of sensors and actuators.

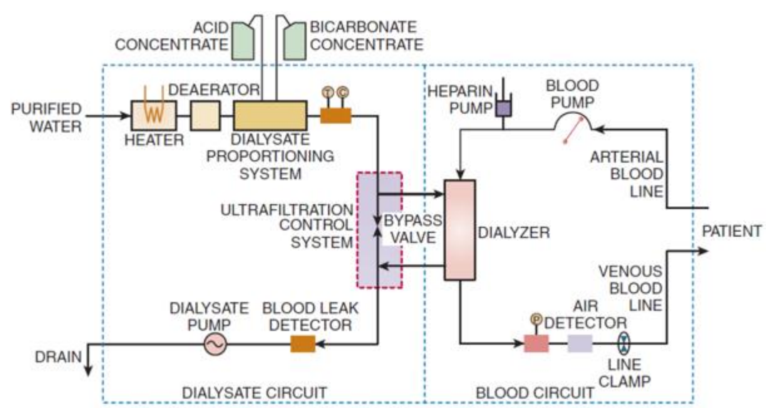

Figure 2: Diagram of the typical system components and layout of a hemodialysis machine. Interface to the patient is through intravenous needles or catheter tubing within a patient's arm.

The dialysate circuit utilizes a heater to bring the solution up in temperature to match patient body heat. A temperature sensor is used to ensure the solution is within a safe range close to the patient's internal body temperature [16]. A conductivity sensor

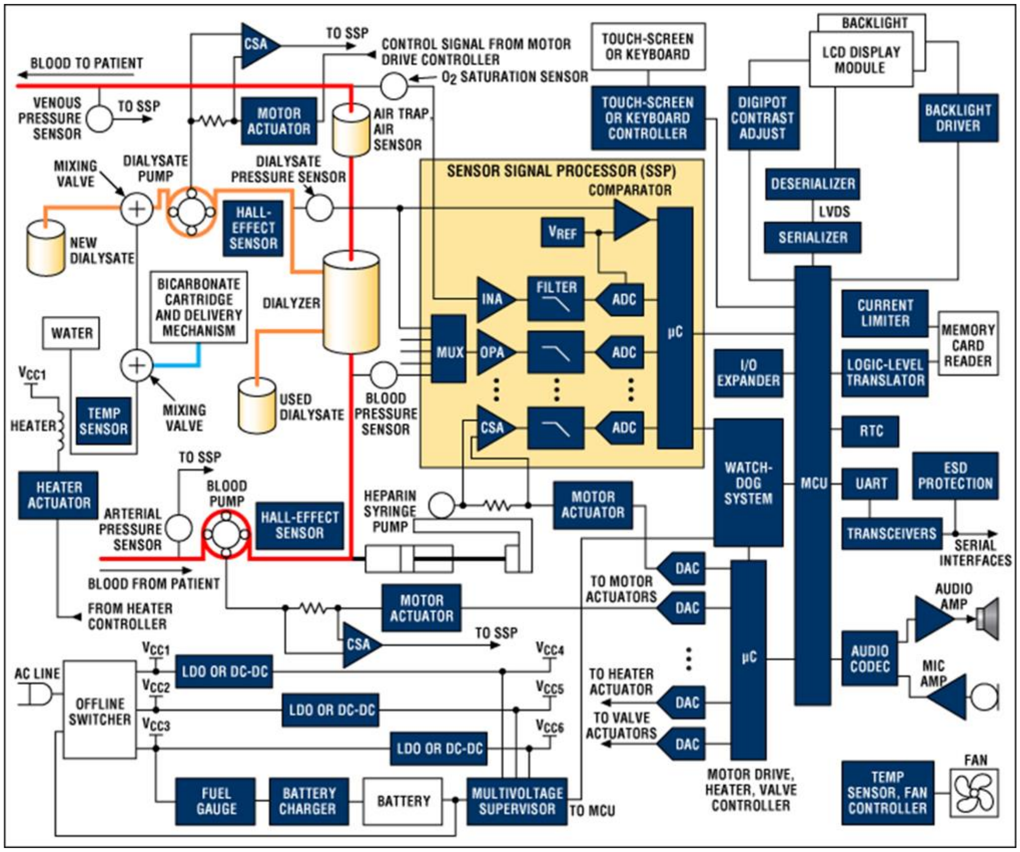

Figure 3: Block diagram of the embedded system for a hemodialysis machine [21]. Numerous processors are used within this system with a main sensor signal processor (SSP) managing the majority of sensor data and actuator functions. LCD displays, audio, and other sensors act as the HMI. DAC's are utilized for interfacing with analog devices. ADC's are utilized to process signals from analog devices. Other external circuitry is utilized to handle signal conditioning and generation for various peripherals.

is utilized to detect alterations in the composition and ensure the consistency of the mixture [17]. This regulated system is passed through the dialyzer for blood purification [8]. The used solution is passed out of the dialyzer to a drain. Since the dialyzer consists of a semipermeable membrane, a blood leak detector is added to this drain line to safeguard against a rupture causing blood loss in the patient [18]. The dialysate circuit is driven by a peristaltic pump which gives high accuracy and flow control in the circuit [19]. Potential sensors which improve safety or redundancy are flow meters to monitor liquid volume, occlusion sensors to detect line blockages, or temperature sensors to track temperature loss through the system.

Drawing from the patient through a modified vein called an arterial fistula [7], the blood circuit utilizes a combination of a peristaltic blood pump and a syringe pump to extract contaminated blood and simultaneously inject an anti-clotting agent called heparin [20]. The contaminated blood is passed through the dialyzer and purified by the semipermeable membrane and dialysate solution from the dialysate circuit [8]. Prior to re-entering the patient, the blood goes through a series of non-invasive tests. To ensure blood is maintained at the proper pressure and prevent damage to a patient's circulatory system, a non-invasive pressure sensor is used [21]. Finally, a non-invasive bubble detector is used to prevent air from entering the patient. Redundant or safety features on the blood circuit may also include flow meters, occlusion sensors, temperature sensors, as well as additional leak detectors at the site of the catheter where blood is drawn from the patient.

Infection is a leading cause of death when undertaking dialysis treatment as bacteria can potentially be introduced directly into the bloodstream [9, 15]. Design considerations must center around reducing infection risk. Between patient treatments, a hot water disinfection cycle is used to cleanse the tubing and sensors within the system. Sensors must be capable of withstanding the high temperatures introduced during this process. Sensors which are invasive, or directly contact the fluid paths, have potential to experience temperature related failures or include features which trap bacteria and are difficult to clean. Non-invasive sensors which function externally to the tubing are preferred as a result.

B. Embedded Hardware

As provided by Maxim Integrated, Figure 3 shows a detailed block diagram of the entire embedded system within a hemodialysis machine [22]. In addition to the dialysate circuit and blood circuit, a third component of these machines is the human to machine interface (HMI). A typical machine will utilize a touch-screen keyboard, display module, audio, and other miscellaneous serial interfaces. Design of the HMI requires an understanding of the operator on the other end. For a traditional hemodialysis machine, nurses and technicians are trained on the operation and usage of the machine. The use of a display allows the operator to easily confirm machine setup, troubleshoot errors, and monitor system status. All components are connected to a sensor signal processor (SSP) which is the main processor driving the entire system. Design of an embedded system requires an understanding of which sensors and actuators are required to accomplish the given task assigned to the system. These sensors and actuators will determine the design of the electrical circuit, as devices typically cannot be directly connected to a processor. For example, coupled with each peristaltic pump is a hall-effect sensor. The output voltage of these sensors varies due to the presence of an external magnetic field, thus providing designers higher output accuracy for smooth motor control [23]. As the output voltage from a hall-effect sensor can be in the millivolt range, the signal is typically too small for a processor, such as an MCU, to natively detect. As such, the output would be coupled with circuitry to switch between a high and low voltage output which an MCU can easily measure. Interfacing with an analog device, such as the dialysate heating elements, requires digital-to-analog conversion (DAC) to allow the MCU to control the device. A common DAC utilizes a binary weighted technique [24], with the generalized equation being

$$V_{out} = -V_{ref} \sum_{x=1}^{n} \frac{b_{n-x}}{2^x} \ volts, \qquad (1)$$

where x is the bit number designator, b is the bit logic state, and n is the number of bits available within the DAC. Utilizing (1) gives precise control of heater temperature depending on the DAC resolution, or number of available bits. Processing an analog signal, such as the measurement from a temperature sensor, requires analog-to-digital conversion (ADC) to allow the MCU to read in pressure measurements. A typical ADC technique involves utilization of a sample-and-hold circuit which uses an internal DAC to approximate the held input voltage. As an analog signal is constantly changing, amplitude error as well as noise can decrease the resolution of a signal. The ideal signal to noise ratio for an ADC is

$$SNR = 6.02N + 1.76dB \qquad (2)$$

where N is the number of bits for the ADC. An SNR greater than 0dB indicates more signal than noise, however designers must be cognizant of how much noise is tolerable as increased levels of noise yields misleading and unpredictable results.

Although some sensors are connected directly to the SSP, many other sensors contain their own processor, such as an MCU, which typically communicates with the SSP utilizing a standard asynchronous or synchronous communication protocol. As noted by F. Mallet, systems tend to combine periodic and aperiodic computations, resulting in a mix of communications which are event-triggered, such as a button press, and time-triggered, such as a sensor reading [25]. Certain protocols are better suited for the different communication triggers than others. The Universal Asynchronous Receiver and Transmitter (UART) protocol is one example which is widely used in data communication as it is highly reliable, capable of long distances, and low cost [26]. This protocol is also excellent for time-triggered communication, as the typical output is a continuous stream of data through a physically connected wire between two devices. Data is sent between devices in this protocol in the form of a packet, as shown in Figure 4. This packet includes synchronization bits, called the Start and Stop Bits, which ensure the receiving processor can extract the data from a continuous stream. Also called the baud rate, both the transmitting and receiving side must agree on the rate at which information is transferred. Each processor will rely on its intrinsic clock source; thus, the communication is considered to be asynchronous. A method of safeguarding against errors in this protocol is through an additional bit, called the parity bit, to check if any particular bit has been corrupted.

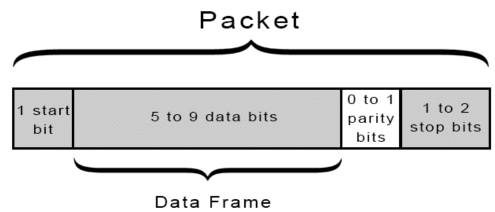

Figure 4: Frame formatting for a UART packet. Designers are free to choose the number of data bits, parity bits, and stop bits based on the needs of their design.

The inter-integrated circuit (I2C) protocol is an example of a commonly used synchronous communication protocol. This is an industry standard used by many electronic devices and embedded systems [27]. Unlike UART, I2C has two physical connections where one is dedicated to data and the other to a clock source, thus communication is synchronized among all devices connected to this source. Data is sent in the form of a message as seen in Figure 5.

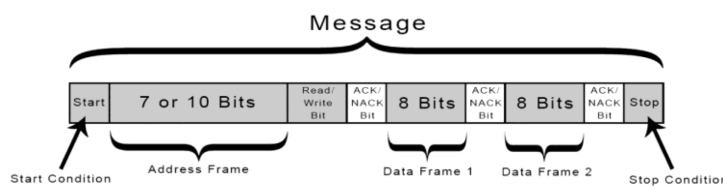

Figure 5: Frame formatting for an I2C message. The address frame allows up to a theoretical 1023 devices to be connected and communicated with. There is no limit on the number of consecutive bytes which can be written.

The Start and Stop bits indicate the beginning and end of the message. Each message begins with an address, which is a unique identifier which allows a theoretical 1,023 devices to be connected together and communicated with. When a message comes to the receiving device, the address stored in memory is compared with the received address to determine if communication should be established. If so, the device responds to the sender with an acknowledge (ACK) bit. Data is then sent in 8-bit data frames, where each subsequent frame must receive an ACK to continue. Once all data has been sent, the stop bit indicates communication has ended and a new device may be communicated with. This protocol is excellent for event-triggered communication, as it can address multiple devices for a short instance. Examples of sensors which utilize these communication protocols are the blood leak detector, flow meter, and sodium monitor.

1) Blood Leak Detector

The blood leak detector used on a hemodialysis machine is an important safety component to prevent patient blood loss in the event of a mechanical failure. The typical design of the sensor includes a photocell and light source such as a light emitting diode (LED) [14]. The basic theory of operation is that the output of the photocell will change resulting from the absorption of light from the presence of blood. Placement of this sensor is at the output of the dialyzer where used dialysate exits. Light is able to pass through translucent and transparent tubing, the blood leak detector is capable of non-invasive detection. As shown in Figure 6, a design challenge for this system is the different wavelength absorption between oxygenated and non-oxygenated blood. Choosing a wavelength light source requires careful consideration as the photocell output will vary based on the type of blood, which can result in an inaccurate reading.

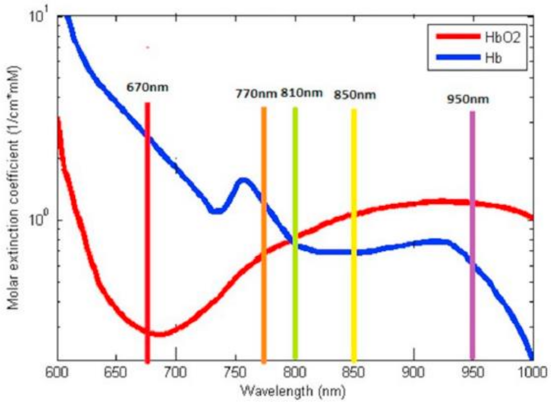

Figure 6: Light absorbance of oxygenated and non-oxygenated hemoglobin cells found within blood at various wavelengths. At 810 nm exists an isosbestic point where the absorption of both cells is the same. Other points at 670nm, 720nm, 850nm, and 950 nm are utilized in [28] for identification of oxygenated or non-oxygenated blood.

Since an isosbestic point exists at 810nm, this wavelength is ideal for a light source attempting to detect the presence of blood [28]. As the photocell output is influenced by light, external sources such as ambient light have potential to impact the sensor reading. To mitigate this issue, the sensor housing must be optimized to minimize ambient light and maximize the angle of incidence of source light to the photocell [28]. Other optimizations are possible by using multiple wavelength LEDs to selectively filter noise from external sources such as ambient light. Due to these design constraints, a blood leak detector is likely to be designed as a stand-alone embedded system which communicates with the SSP. An embedded system designed for this application may use an MCU with a DAC to control the light source brightness by varying the bit values in (1) and an ADC to process the photocell output. This type of sensor is typically designed for I2C connection as it is an event-driven sensor.

2) Flow Meter

Maintaining higher blood flow rates has been associated with a higher patient quality of life and decreased hemodialysis side effects such as nausea, vomiting, and lack of appetite [29]. Sensors for flow measurement are used to determine pump output as a result. Ultrasonic technologies are an optimal solution for flow rate measurement due to their high reliability and non-invasive capability [13]. Typical sensors will place two piezoelectric transducers mounted for measurement upstream and downstream to the liquid flow by measuring delta time-of-flight (ΔToF), as shown in Figure 7.

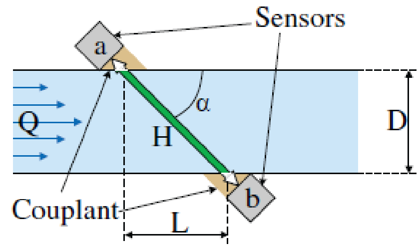

Figure 7: Positioning of ultrasonic transducers for time-of-flight measurement in relation to liquid flow.

One piezoelectric transducer is typically excited by an oscillator circuit which has been tuned to match the natural frequency of the piezoelectric material. This creates an ultrasonic wave which traverses the liquid path to the receiving transducer. The receiving piezoelectric transducer generates a small electrical response which must be amplified and filtered in order to be acquired by the processor. To calculate upstream and downstream, both transducers must perform the action of transmitting and receiving. Measurement occurs after a time delay resulting from the speed of sound travelling through the housing material, tubing, and liquid. As shown in Figure 8, the upstream and downstream waveforms are captured with the time difference between zero crossings yielding the ΔToF.

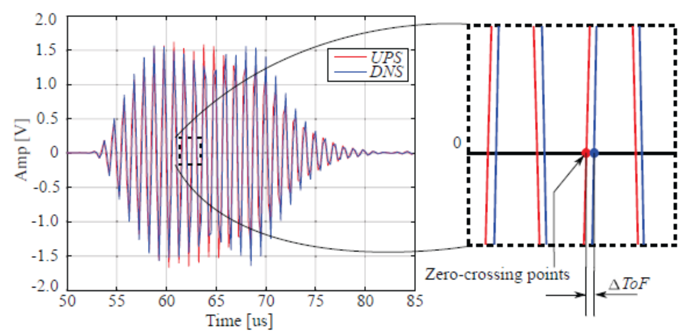

Figure 8: Upstream and Downstream measurements are captured by high precision ADC. Zero crossing of each is used to determine the time of flight which is then used to calculate velocity.

Traditional circuitry in this system requires oscillation circuits, amplifiers, and DACs for the processor to generate and measure signals from the piezoelectric transducers. These signals are processed by software to calculate flow velocity. As the sensor is time-based, the typical output will utilize an analog signal or communication protocol such as UART.

C. Embedded Software

Modern embedded systems require a combination of hardware and software for full functionality. A processor is only as effective as the software running within it. Behind the hardware detailed in Figure 3 is a complex series of codes written to process the various sensor data. Starting with the SSP, embedded software will perform the necessary checks to ensure the system is capable of operation. One potential sensor not explicitly shown in Figure 3 would be a magnetic sensor to detect if a lid is open. Within the software is a check to determine lid status prior to operation of the machine. During machine operation, software will also store sensor data, such as temperature, flow rate, or patient metrics. This stored information can be utilized to improve diagnostic and therapeutic procedures to better facilitate hemodialysis treatment [30]. As discussed in [13], ultrasonic flow meters utilize piezoelectric transducers to generate signals for determining flow rate by utilizing the ΔToF. Figure 7 shows the software flowchart for the processor within an ultrasonic flow meter sensor. Starting with parameter setting, the software configures the processor hardware for proper generation of electrical oscillations to excite the piezoelectric transducer. Depending on the tube material and gap between transducers, software will wait for the time between transmitting and receiving signals to begin data acquisition. This occurs in the upstream and downstream direction in relation to the liquid flow. The particular software written in [12] gives designers the option for internal or external processing of transducer data to calculate the flow rate, Q.

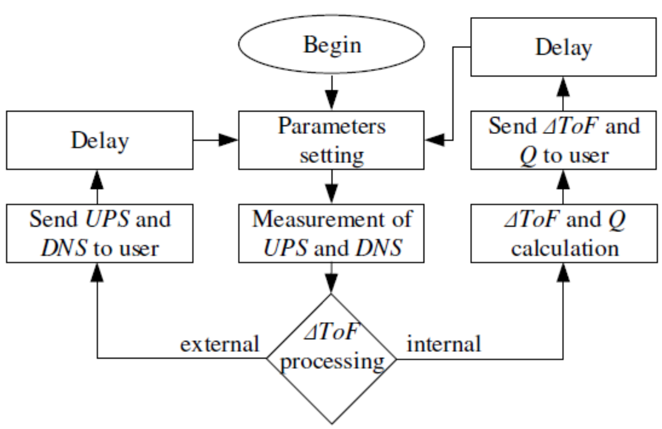

Figure 9: Software flow chart for flow measurement utilizing ΔToF calculations. Users have the option for internal or external processing of transducer data to calculate the flow rate, Q. In both instances, a delay is built into the software to compensate for potential ringing or reflection of ultrasonic waves [13].

Software is responsible for the processing of sensor data from numerous sources. Although embedded hardware is capable of simplifying communication protocol implementation, software is still required to grab the data and perform necessary operations upon it. Software instructions are stored in memory. The processor must fetch the instruction, decode, then execute the instruction. Understanding how the hardware reacts is imperative to proper algorithm implementation. For example, an FPGA may be coded for parallel processing while an MCU is only capable of pipelining code instructions. As this can have drastic performance and speed implications, software engineers must be cognizant in their system designs. Beyond rigid algorithms, code is written to track patient metrics over time and track patient wellbeing. Since hardware is typically limited in memory size, designers will incorporate networking capabilities to access remote storage. Reading and writing to remote data repositories also gives doctors access to patient data without needing to physically observe the patient or wait for patient metrics to be manually entered into the system by an operator.

Writing embedded software can be different from writing desktop or server applications as there are often strict resource limitations, such as memory space, communication bandwidth, power consumption, and hard real-time requirements. As such, embedded software developers rely heavily on run-time debugging tools such as oscilloscopes, logic analyzers, and circuit emulators. Effective software writing techniques revolve around maximizing the capabilities of the hardware to solve challenges as efficiently as possible. During data acquisition, one technique is to grab the data from an input once, called polling, and perform an action or calculation based on the polled value. In critical systems such as dialysis, it is more efficient to continuously scan the input data and average or filter the results depending on the sensor. Understanding hardware limitations is important in software development. An MCU, for example, is only capable of executing instructions in order. If there is a large number of inputs to poll, there is potential to lose data between the time the first sensors polling instruction is called to the last. Even if the instructions are pipelined to execute as fast as possible, there will always be a time delay which could potentially result in lost critical data. A technique within the hardware of some MCUs is called interrupting, where hardware tells the CPU to jump to a different section of code. On the other hand, an FPGA is general purpose enough where code sets can run in parallel, thus the need to calculate scan time is mitigated.

1) Blood Leak Monitoring

Dialysis centers have the potential for numerous patients to be undergoing treatment simultaneously. Due to the potential for failure resulting in blood loss, it is imperative for the machine to monitor for blood leaks. As the quantity of patients tend to outnumber nurses, a need for a wireless central monitoring system exists [31]. One potential location for a blood leak to occur is at the site of the IV into the patient's arm. Since the leak is not localized to the dialysis machine, an embedded system capable of wireless communication is necessary. As designed by Hsiang-Wei Hu in [31], a sensor patch designed as a series of loops "utilize the principle of open circuits and parallel resistance." Liquid contact with the various rings result in a closed circuit which is measured by the MCU. The system uses Bluetooth Low Energy (BLE) which communicates data to a gateway to pass the information to a network. BLE is a wireless protocol which works well in short distance wireless communications. It also has an advantage of being low power, thus devices are capable of operating on battery power. The main limitation of BLE comes from the payload size which software designers are capable of working with [32]. The standard data packet contains a 31-byte payload with 20 bytes being application specific. In the case of a blood leak monitor, a sample packet shown in Figure 8 requires 12 bytes to transmit all necessary data.

PROTOCOL VERSION	SERIAL NUMBER	SENSOR ID	PATCH OUTPUT	SYSTEM STATUS	ERROR CODES
1 BYTE	4 BYTES	1 BYTES	4 BYTES	1 BYTE	1 BYTE

Figure 10: Sample BLE data packet for a catheter blood leak detector. This assumes a maximum application payload of 20 bytes.

As changes to the packet can impact or break wireless communication, the first byte of protocol version is checked by the receiving end to confirm the correct format will be sent and 1 byte indicates a potential 255 changes are possible. Serial number indicates a tracking method for manufacturers to identify particular sensors deployed in the field. 4 bytes allows for over 4 billion potential devices to be built. Sensor ID is used for local identification to allow operators to quickly identify which patient may need attention. The patch output is the raw instantaneous analog output of the sensor and is formatted as a 32-bit IEEE 754 floating point number. This number would typically not be seen by operators, but rather used in data tracking and diagnostics. The system status is decoded to give operators information about the device, such as presence of leaks detected, alarm state, or other pertinent information. Finally, the error code byte is necessary to give diagnostic data if an internal or external issue occurs. The results of the system in [31] demonstrated accurate and reliable transmission of information packets, thus allowing staff to efficiently monitor patients.

2) Patient Monitoring System

The Internet of Things (IoT) represent systems which are capable of data recording through a local or wireless network. In a hemodialysis system, IoT capability enables patients and healthcare providers to access daily reports regarding patient status [33]. Hemodialysis is not a one-size-fits-all solution for CKD, and each patient will have nuances in aspects such as timing and dosage. Not included in the typical embedded system diagram in Figure 3 are the secondary systems which a patient may also be connected to. Sensors which monitor crucial patient parameters such as body temperature, blood pressure, glycemic index, or electrocardiography allow healthcare providers to fine-tune the hemodialysis machine to better suit the needs of the patient [33]. The system design by M Zainol et al utilizes an embedded system with an MCU, BLE, and IEEE 802.11 (Wi-Fi) integrated circuits for wireless heart monitoring during hemodialysis. Connection between integrated circuits utilizes the I2C protocol. A webpage is used for patients to monitor sensor readings in real time. The Transmission Control Protocol (TCP) and Internet Protocol (IP) are utilized within the Wi-Fi integrated circuit to transfer data from the sensor to the webpage. As shown in Figure 11, the TCP/IP model is set up in concurrent layers.

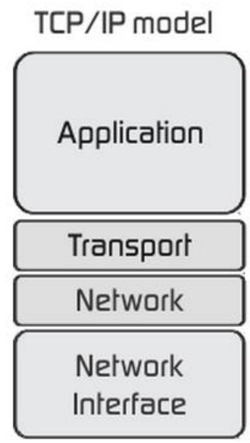

Figure 11: Diagram of TCP/IP model layers. Each layer contains a set of standard protocols for interfacing with the next or previous layer.

The first layer, known as the Network Interface Layer, handles the physical infrastructure to allow connection to the internet, as well as conversion of data into a transmittable format. The second layer, called the Internet Layer, is concerned with establishing the connection between devices and ensuring proper data formatting. The transport layer is third and moves formatted data from one source to another. Finally, the application layer is the physical interface where users can access the data put on the network, such as the webpage set up in [33]. The embedded system in the patient monitoring system contains a microcontroller with the necessary hardware and software for wireless implementation. The network interface utilizes Wi-Fi. The device is set to a specific IP address which the webpage application is able to locate. The transport layer will check data packets for errors relating to wireless transmission and discard if found. This combination of hardware and software allows for rapid development of wireless devices such as the patient monitoring system.

III. At Home Challenge, the Future of Embedded

Two prominent non-medical barriers to home hemodialysis are economic barriers and insurance challenges [34]. Additionally, FDA standards are typically more stringent for products designed for home use as they cannot guarantee monitoring or usage by a trained individual within a controlled environment. Designs must meet standards described by the IEC and, for medical devices, must meet or exceed IEC60601-1 specifications [35]. While these regulations do not dictate the design of a hemodialysis system, a designer must consider methods to ensure safety, reliability, as well as economic and insurance barriers a home system poses. The major economic barriers for home hemodialysis are associated costs and complexity. Being employed or having employer insurance was found to be positive predictors of home hemodialysis utilization [34]. Individuals with private insurance were more likely to choose home dialysis compared to those with federal or state funded instance such as Medicare. When analyzing what is not covered by Medicare for home hemodialysis, a significant expense is the lack of coverage for training or dialysis aides [36]. A complex machine which requires significant training, or a machine which requires secondary assistance, will certainly contribute to the economic barrier of home hemodialysis as a result of non-private insurance. Another challenge with a home solution is reliable access to purified water. Factors such as quantity of total dissolved solids, bacteria, chlorine levels, lead presence, and hardness can vary between locations, thus a machine must contain several steps of filtration to ensure patient safety without compromising size or cost. These barriers, as well as higher standards for FDA approval, pose significant challenges in designing a home hemodialysis machine.

A. Cost, Complexity, Operation

Historically, dialysis machines were higher cost due to the cost of the technology within them [1]. Significant advancements have been made in embedded design to reduce the size and cost of embedded systems. While older systems would attempt to funnel all sensors and actuators to one large processor for cost efficiency, modern embedded systems are cheap enough to have multiple smaller processors which are typically lower cost than their larger counterparts. Companies which specialize in sensor design may utilize their own embedded systems as part of the signal processing unit, thus further decentralizing processing. Additionally, as the physical size of semiconductors decreases, the capability to pack more features into a single integrated circuit allows for a natural reduction of the number of semiconductor components required in a design. In many cases, these improved designs also result in higher power efficiency. At a certain point, sensor efficiency increases where it is capable to be operated from a remote power source such as a battery. This can further lower costs by reducing physical copper connections to a high voltage source which requires additional circuitry to regulate. Although current battery technology is not capable of powering an entire hemodialysis system without being large, costly, and cumbersome, reduction in power within the embedded system and improvements in battery technology could produce an entirely wireless device.

Operation and ease of use are significantly important for an at-home system to be viable. In-center hemodialysis machines are frequently cleaned by a technician to ensure proper sanitation during operation. In development of a home solution, a preference for non-invasive technology or disposable sensors increases as a way to make sanitation easier. Developing new systems which are capable of non-invasive measurement of signals which were previously measured invasively can also reduce costs for the patient. In terms of physical operation, designing a user interface that is intuitive and familiar can reduce the amount of training required for operation. For example, integration of wireless capabilities to pair the device with a patient's smartphone will give them a familiar medium to operate their machine. A Graphical User Interface (GUI) with illustrations, text, and videos for different operational steps will improve operation. A challenge with connecting to the patient's smartphone, however, is ensuring a reliable paired connection [31]. Additionally, design considerations must account for those who do not possess a smartphone, thus having information located on the machine is essential.

B. Data and Training

A barrier from state or federal insurance is lack of coverage for dialysis aides who can monitor and manipulate the machine for the needs of the patient [36]. A home solution will require a patient also be the technician who is capable of set up configuration, operation, and maintenance of the system. Due to the machine complexity and risk of mistakes, design and training are essential. B. Shahbazi notes that stored information can be utilized to improve patient education and training [30]. Limitations in current hardware processing speeds can limit the quality of displaying stored information. Higher speed processors will allow graphical user interfaces to display better resolution images and videos which can guide the patient through operation. Designing augmented reality would also be an excellent tool a future system could utilize. Overlaying information onto the machine can aid patients in identifying issues or with proper alignment during installation of parts. For example, the patient will be tasked with properly aligning and inserting the IV needles into the arterial beam fistula in their arm [21]. A tool which is capable of identifying this fistula and giving the patient a visual reference for alignment would aid in proper installation. With the absence of a technician to operate and maintain the machine, physical operation should require minimum user interaction and aim for autonomy in functionality, error handling, and progress tracking. Miniaturizing sensors to fit onto a single disposable cartridge will simplify maintenance for the user. Utilizing machine automation to confirm setup and begin operation takes the burden off the patient.

Future systems will utilize efficient techniques in collecting and managing data. Saving data wirelessly through a local network allows a report of detailed daily patient and machine statuses to be generated and viewed by the patient, aide, or their doctor [33]. Improving wireless technology to be lower power and more accessible will give patients further ability to be self-sufficient. Adequate warning systems and redundancy are necessary to properly alert the patient of an issue. A combination of audible and visual alarms can notify a user of an immediate problem. A challenge for a home solution would be proper training on handling these issues. Utilization of self-learning algorithms, or Artificial Intelligence (AI), could potentially allow users to avoid manually correcting issues themselves.

C. FDA Approval

Designers must be cognizant of the high standards required for FDA approval of a system intended for home medical use.

Electromagnetic interference (EMI) poses a significant challenge as there is potential for sensors and actuators to fail. EMI can be natural or manmade, with potential EMI sources being microwave ovens, ESD guns, or RF transmitters [37]. Sensor accuracy can be impacted by EMI which can have catastrophic results. EMI can add noise to (2), thus resulting in a sensor reporting values incorrectly. Current techniques for EMI mitigation include filtering, circuit partitioning, grounding, and enclosure shielding [37]. Incorporating these features in future devices will reduce complexity and increase sensor robustness. Mitigating EMI is a significant challenge in embedded systems. Another aspect of design which impacts certification is circuitry power. Presence of high voltage or current which can potentially cause harm must be well controlled and isolated. Lower power and higher precision instrumentation will improve the safety and accuracy of embedded systems.

An important aspect in the design of a home hemodialysis machine is consideration for cleaning. Residual blood or contaminants within the system can have a catastrophic impact on patient health and the functionality of the machine. Invasive sensors pose challenges as they must be hermetically sealed to avoid potential short circuits causing damage to the device. Invasive sensors also present an increased risk of infection as bacteria can become trapped within features of the sensor. A hot water cycle is commonly used, however invasive sensors are more prone to failure due to repeated high temperature cycling. As a result, many medical sensors utilize disposable cartridges which do not require cleaning, however this can be cumbersome and costly for a patient. As a result, non-invasive technology is preferrable to reduce cost over time and avoid cleaning related damage risks. Additionally, water must be purified to meet minimum acceptable standards for dialysis treatment. Systems which generate reliable clean water automatically represent a challenge that would improve patient well-being and machine availability [1].

D. Educational Challenge

Due to the severity of CKD and the impact on patient QoL, rapid development of a home solution is imperative. The scale and complexity of such a machine requires skill and experience to create. Training new engineers to implement modern hardware and software solutions can be difficult due to their lack of experience. Traditional embedded systems education occurs in a course which studies the hardware and software of one system [38]. I. Ibrahim et al state that three main challenges from this approach are student, lecture, and content related. Student motivation and interest must be developed through intriguing and relevant challenges. Lectures must be relevant enough regarding new technology to prepare students for entry to the work force, but general enough to “teach intuition about the physical realities of embedded systems” [38]. Finally, projects within the curriculum must engage students, educate on embedded topics, and inspire curiosity for independent learning. A major educational challenge in teaching embedded hardware and software is on the creation of content which is practical and durable. Emphasis on foundational theory reduces the ability for a student to gain intuition to solve real challenges, however emphasis on modern technology risks students only receiving training with near-term value [38]. Along with challenges for the student, lecture, and content are challenges with evaluation. Evidence shows that many readiness measures do not sufficiently predict an individual’s ability to solve real world challenges, even if it is effective at measuring academic performance [38]. I. Ibrahim et al concludes that improved course and curriculum structure is required to overcome these challenges.

IV. ADVANCEMENTS IN EMBEDDED

Hardware advancements have moved towards single integrated circuit solutions for complex problems. These single chips incorporate the external circuitry typically required to control a sensor or actuator as an internal component of the processor. For example, Texas Instruments has developed a MCU which specifically handles the generation and measurement of piezoelectric transducers for calculations by utilizing a programmable pulse generator and high speed ADC [13]. Development of this microcontroller has given designers flexibility and lowers circuit costs by reducing the number of required hardware components contained within the circuit. Wired connections are made between the transducer and MCU greatly simplifying design and troubleshooting requirements when in development of an ultrasonic flow meter. In addition to simplifying hardware, the Texas Instruments chip is capable of internal calculation of flow velocity once the device has been sufficiently configured. Other single chip solutions being developed also include the necessary components for wireless communications, such as BLE. Designers no longer require a separate processor to handle sensor and actuator data as companies such as Bluegiga develop MCU’s capable of handling that data as well as wireless communication. These devices also include hardware for communication such as UART and I2C. The Bluegiga MCU’s contain an additional advantage by providing “high-level development scripting languages that can significantly reduce development time” [32]. Another benefit of single chip solutions is potential for systems to be lower powered, thus being capable of remote operation using batteries. A wearable hemodialysis machine would give patients significant mobility; however, energy efficiency must allow battery operation to extend beyond the duration of the treatment [8]. Outside of single chip hardware, costs for robust and higher accuracy sensors have reduced [1]. This reduction of costs has allowed a rise in equipment automation to perform tasks at a higher accuracy. C. Graansma notes that “the use of automated equipment [improves] quality control, reduces labor costs, and reduces the exposure of staff to harmful chemicals.”

Advancements in software development has seen a rise in AI techniques such as machine learning. Traditional methods of solving challenges involves development and application of a series of rigid algorithms, whereas artificial intelligence comes from a group of algorithms which are capable of modifying themselves to create new algorithms in response to learned inputs and data. The machine learning process simulates the learning mechanisms of the human brain by processing data, recognizing patterns, and calculating probabilities electronically

[39]. The three principal models of AI are supervised learning, unsupervised learning, and reinforcement learning. Supervised learning requires a labeled dataset which links input and output data. A non-labeled dataset is used to validate the success or failure of the algorithm. Unsupervised learning relies on the algorithm to find patterns and correlations between unlabeled data. Algorithms can cluster data with similarities which also differentiate from other data points. The reinforcement learning model requires an external observer to interpret and rate the solution developed by the AI. Depending on the solution, the observer provides positive or negative feedback which will influence the output of the next iteration of data. Machine learning techniques are greatly beneficial to hemodialysis. For example, if a doctor observes patient heart rate and blood pressure increasing towards the end of treatment, they are tasked to troubleshoot the cause of duress. They may conclude that bicarbonate is running low, thus purification is less efficient and results in patient stress. Unsupervised AI would act as the doctor by analyzing irregularities in the system to draw the conclusion that blood pressure has risen as a result of the dialysate mixture being diluted. Utilization of AI can assist with personalized decision making, diagnosis support, and prediction of treatment outcomes.

The application of BLE in a blood leak detector as designed by Hsiang-Wei Hu utilized a secondary device to transfer data to a secondary device with network access. Implementation of IoT allows nurses to be immediately notified of potential issues as the patients are able to be monitored in real time [31]. This is a major advantage over prior systems which utilized audible alarms which may or may not be heard by the nurse. BLE allows quality of care to increase without adding operational burden to the staff. Another advantage of BLE which would be effective for home hemodialysis is easier integration to communicate with a patient's smartphone. Improvements in IoT software allows smart phones to act as the gateway to transferring diagnostic data to the network for further analysis. Applications developed on the smartphone would allow patients or others to monitor vital information regarding the treatment and give a familiar mode of interfacing with the hemodialysis machine.

V. Discussion and Future Considerations

Today's embedded systems are capable of facilitating home hemodialysis; however, it requires a deep understanding of embedded and multi-board systems to overcome the technical challenges involved. New software technologies utilize IoT to allow data to be easily accessible for diagnostics and monitoring of patient metrics. Implementation of AI allows improved decision making, diagnosis support, and prediction of outcomes which is beneficial to the patient and doctor. Advancements in hardware allow a reduction of cost and potential for battery powered operation by utilization of well-designed single chip solutions to challenges. Future advancements in embedded systems will increase the accessibility of home hemodialysis. Over time, systems will have more functionality at lower costs, as well as methods to improve ease of operation. New technology will be developed to facilitate non-invasive sensing where traditional invasive methods are used. Wireless technology will improve to make data more accessible. These and other advancements will be beneficial in seeking FDA approval for a machine, as well as reduce the impact a patient may feel if they do not have premium insurance. As embedded hardware and software improves, home hemodialysis machines will be more readily available for patients. CKD is a leading cause of death in the US, thus transitioning to a home solution will improve patient quality of life and reduce morbidity. Quality of life will improve by providing a comfortable environment for treatment as well as reducing scheduling and travel requirements. Reduced mortality will result from easier access to longer or more frequent sessions. As a relevant and complex challenge in industry, hemodialysis machines are an excellent candidate for the training of new engineers. An improved curriculum structure could include the connection of multi-board systems to give students experience with large projects that utilize multiple sensors. Such a system would also give students a relevant way to correlate written software to hardware needs. Future research should focus on the design of a multi-board educational tool system which sufficiently enhances student education by overcoming the challenges of student motivation, interest, connection between topics, and connection between embedded systems and other disciplines. Such a system will allow students to be better prepared for the challenges in developing high performance embedded systems.

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