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Sustainable Mannequin Robotic Telepresence for Maternal Mortality Reduction in Sub-Saharan Africa

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Abstract: This study presents a cost-effective, energy-efficient and eco-friendly solution that could significantly reduce maternal mortality in Sub-Saharan Africa. Low-income countries can exploit the huge potential of ICT to effectively handle the challenge of shortage of qualified medical consultants and specialists which has become a serious threat to sustainable development in the region. Unfortunately, available telepresence solutions in telemedicine have extremely low penetration in emerging economies due to relatively exorbitant costs and lack of reliable power grid. Therefore, we developed a context-adaptive robotic telepresence, Sustainable Mannequin Robotic Telepresence (SMART) which is well-suitable for remote ward rounding in Sub-Saharan Africa. Two IP network cameras that communicates over the Internet using Wi-Fi transceiver module available on raspberry pi were housed in a plastic mannequin to minimize cost. The system was designed to operate on solar PV system or free energy alternative source to ensure availability of required electrical power at low cost. SMART system gives a better impression of the physical presence of a physician. The results of the comparative cost analysis of SMART with robotic telepresence available in the market showed that our system is more affordable with better efficiency thus increasing the chances of maternal mortality reduction among underserved populations.

Key words: Maternal mortality, robotic telepresence, telemedicine, Sub-Saharan Africa, sustainable development

INTRODUCTION

Predominantly in developing countries, women of reproductive age most often lose their lives to problems associated with pregnancy and childbirth. According to world health organization (UN, 2015 a, b), maternal mortality refers to "the death of a woman while pregnant or within 42 days of termination of pregnancy, irrespective of the duration and site of the pregnancy from any cause related to or aggravated by the pregnancy or its management but not from accidental or incidental causes". Maternal mortality ratio is an important indicator of sustainable development; in fact its reduction is the first target of goal 3 of the 2030 united nations sustainable development goals (UN, 2016a).

The increasing rate of maternal mortality received a global attention when world leaders called for a reduction of 75% between 1990 and 2015 through the acceptance of the Millennium Development Goals (MDGs) at the Millennium summit in September, 2000 (UN, 2016a). Despite, the concerted efforts geared towards the realization of this goal there were yet about 330,000 maternal deaths worldwide at the end of 2015. Approximately 99% of these deaths took place in rural areas of developing countries where majority have no access to quality health services (UN, 2016b). Sub-Saharan Africa alone accounted for approximately 201,000 maternal deaths, hence the region with the highest maternal mortality ratio (Alkema *et al*., 2016). In order to ensure healthy lives and promote 'well-being for all' at all ages, the international community has shown a renewed commitment towards reducing the global maternal mortality ratio to <70 per 100,000 live births by 2030.

In view of this most high mortality countries need to seek practical means of meeting the ambitious Sustainable Development Goal (SDG) target (UN, 2015a, b) and ultimately eliminate preventable maternal mortality. As a point of duty, Sub-Saharan African countries will need to pursue a drastic maternal mortality reduction at a rate of at least 7.5% yearly (Alkema *et al*., 2016). To achieve this there is an urgent need to properly understand the major causes and adequately proffer effective and practical solutions.

A consistently wide difference has been maintained between the maternal deaths recorded in developing countries and the developed world as shown in Fig. 1. Between 1990 and 2015, the difference in maternal mortality ratio was in the range of 250 and 400. This is traceable to inequities in access to health services and it

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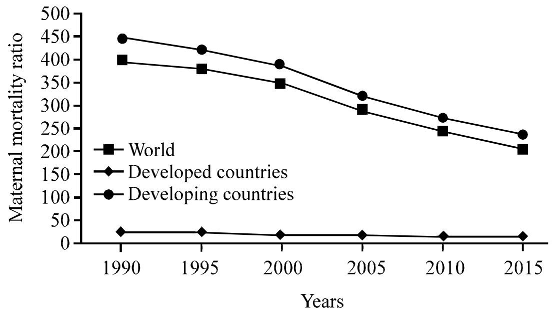

Fig. 1: Global assessment of maternal mortality reduction between 1990 and 2015 (WHO, 2016)

reveals the gap betwee n the rich and the poor. Apart from the large disparities between countries, the number also varies significantly within countries between women with high and low income and those women living in rural versus urban areas (WHO, 2015a, b). However, as depicted in Fig. 1, reduction in the maternal mortality ratio in developing countries significantly translated into reduction in the global index. Say *et al.* (2014) reported that nearly three-quarter of all maternal deaths are due to severe bleeding, infections, high blood pressure during pregnancy, complications from delivery and unsafe abortion. Although maternal, newborn and child deaths result from causes that can be adequately treated by a package of well-known interventions (UN, 2010; Black *et al.*, 2010; Sousa *et al.*, 2012), shortage of well-trained and motivated health workforce hamper the delivery of essential and life-saving interventions designed to avert these deaths (Chen *et al.*, 2004; Buchan and Couper, 2013). Even in countries where sufficient numbers of health workers are available they are mainly concentrated in urban centers while severe shortages exist in rural communities where majority of the population are marginalized (Jansen *et al.*, 2014; Smith *et al.*, 2013).

With the present situation depicted in Fig. 2, low-income countries should begin to exploit the huge potential of the recent advances and widespread of modern Information and Communication Technologies (ICTs) to address serious challenges facing the healthcare sector in the region. One of the applications of ICTs for health care delivery is known as telemedicine. In a broad sense a report of the WHO group consultation on health telematics (WHO, 2015, 1997) defined telemedicine as “the delivery of health care services where distance is a critical factor by all health care professionals using information and communication technologies for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation and for the continuing education of health care providers all in the interests of advancing the health of individuals and their communities”.

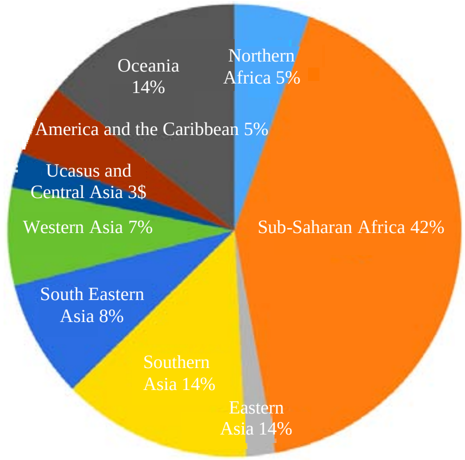

Fig. 2: Regional Maternal Mortality Contributions in 2015

Regions with inadequate infrastructure mainly use telemedicine pplications overcome eographical barriers that are commonly encountered when trying to connect patients to specialists, referral hospitals and tertiary care centers that are not in the same physical location (Heizelmann *et al.*, 2005). Real-time video telecommunication capabilities of telemedicine (Craft, 2001) can be harnessed by health workers, medical consultants and specialists to deliver health care services to patients in remote places without being physically present. The service may be in form of direct patient care, health education and clinical consultation in critical care, transmission of dermatologic or radiologic images or real-time video distant-monitoring support in the intensive care unit (Poropatich *et al.*, 2006).

A number of telepresence initiatives have been developed for health care applications. Remote tele-consultative service offered by Grundy *et al.* (1977) using a two-way audiovisual link produced a better clinical and educational effect than the telephone (Grundy *et al.*, 1982). eICU (Celi *et al.*, 2001) a dedicated facility designed for intensive care unit, allowed a consultant to supervise and monitor patients in different locations at the same time, reducing mortality and cost (Rosenfeld *et al.*, 2000; Breslow *et al.*, 2004). Telemedicine have been applied for trauma and neurology consultative services where there are no resident specialist (Ricci *et al.*, 2003; LaMtonte *et al.*, 2003; Shwamm *et al.*, 2004; Ickenstenin *et al.*, 2005; Audebert *et al.*, 2005). However, the adoption of telemedicine applications in marginalized communities is faced with the problems of complex human and cultural factors (Craig and Patterson, 2005), lack of proof of economic benefits and cost-effectiveness and legal considerations (Al-Shorbaji, 2008; Kifle *et al.*, 2005; Swanepoel *et al.*, 2010).

Robotic telepresence has the capacity to enhance the effectiveness of telemedicine by creating an impression of the physical presence of a physician at remote location. It accomplishes this task using a mobile robotic mechanism that is capable of real-time audiovisual communication (Ellison *et al*., 2004; Thacker, 2005; Vespa, 2005; Vespa *et al*., 2007; Gandsas *et al*., 2007; Chung *et al*., 2007; Manecke *et al*., 2007; Ellison *et al*., 2007). Considering the high level of extreme poverty in Sub-Saharan Africa most of the available technologies in this regard are relatively unaffordable for deployment in the remote locations. Also, the unreliable power grid in this region where a good number of places in the rural areas are not connected at all, may likely hamper the sustainability of such system.

In this study, we developed a Sustainable MAnnequin Robotic Telepresence (SMART) system as an enabling platform for effective access to better health care delivery among underserved populations. Materials used in the implementation of the robotic telepresence system are locally sourced and readily available. This makes the platform relatively cost-effective when compared to state-of-the-art systems available in the market. To properly handle the problem of lack of electricity and global warming effects, the entire system is designed to operate on a solar PV System or a free energy generator.

MATERIALS AND METHODS

System architecture: Sustainable Mannequin Robotic Telepresence (SMART) system is robotic system that is remotely controlled using a webbased software application that runs on the Internet. The hardware part of the system (IP network cameras, mini-computer, wireless network transceiver, audiovisual system) are entirely enclosed in a plastic mannequin. The semi-humanoid approach is aimed at creating an impression of the physical presence of the medical consultant or the specialist as the case may be. Also, plastic mannequin are relatively cheap and this will reduce the cost of the overall system. The plastic head can be molded to correctly represent the real head of the medical practitioner attending to the patient from a remote location. The mannequin is dressed in the regular attire of health worker on duty.

Two IP network cameras are fixed into the eye sockets of the mannequin robot. One of the IP cameras is intended to enable remote access for a distant-consultant while the other is reserved for a specialist so as to facilitate professional collaboration targeted towards reducing the number of maternal mortality in rural areas of developing nations. The IP cameras are securely accessible to the health professionals via the web server application. For the audiovisual sub-system a microphone is fixed on the neck section of the mannequin. With this, the remote users can easily pick up acoustic signals

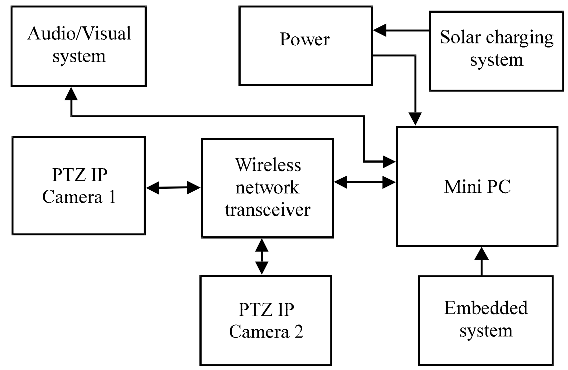

Fig. 3: Block diagram of SMART stystem

Fig. 4: SMART system mobile applicatin

from the clinical ward for effective communication. The microphone is quite sensitive to vibrations thus providing good acoustic quality. The well-perforated chest part of the mannequin houses the speaker. A fourwheel movement support is designed at the base carriage and operated by a 12 volt DC electric motor. The software application runs on the pre-programmed raspberry Pi located within the plastic mannequin. The system is connected to the Internet via a Wi-Fi communication link established between a high-speed access point and Wi-Fi adapter on the raspberry Pi. Remote users can log in to the system using different platforms such as smart devices, desktop computers, laptops, PDAs, etc. The block diagram of the SMART system is shown Fig. 3 and 4 community health workers available in remote places will assist the medical experts in collecting vital

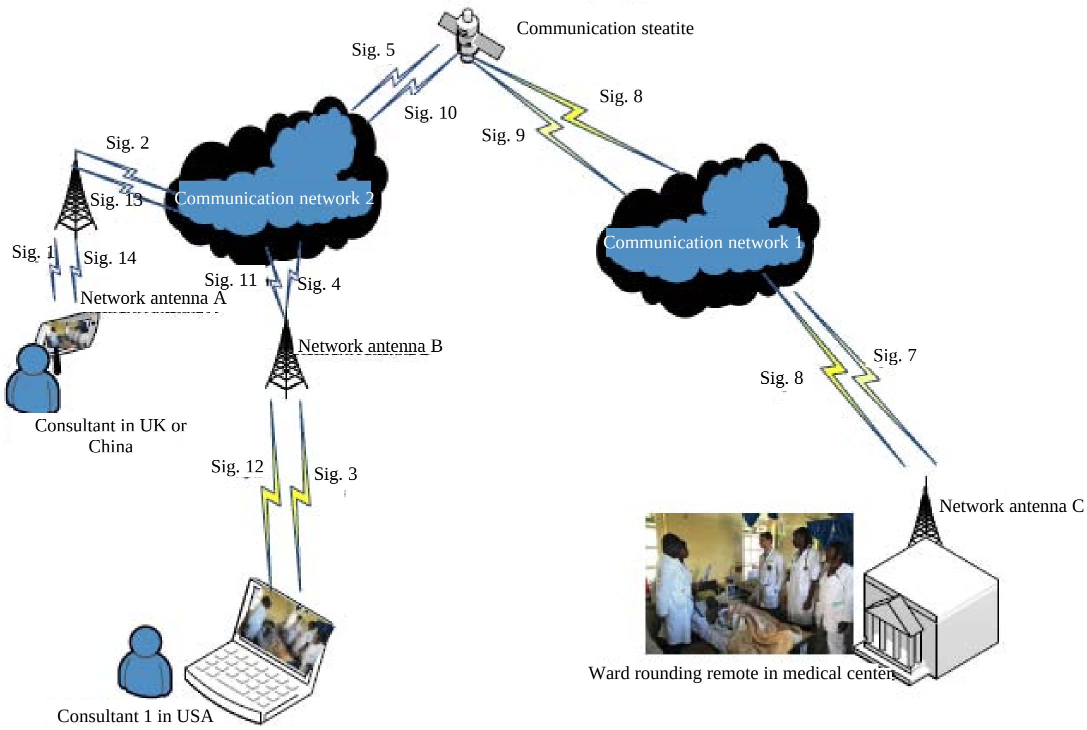

Fig. 5: Architecture of sustainable mannequin Robotic telepresence (SMART) system

health information and records of patients whose cases are critical. The system allows real-time audiovisual communication between the medical professionals, the community health workers and the patients. The pan-tilt-zoom capability of the IP network cameras enables the remote consultant and specialist to gain a complete view of the hospital ward and if necessary zoom in to focus on a particular part of the body of the patient with no assistance from the community health workers.

Web server software application: A client-server model was used for the web server and Hypertext Transfer Protocol (HTTP) forms the webpages. This module links the remote user to the SMART. The Apache webserver runs on a dedicated computer and also on the raspberry pi. The program flow for the web-server in (Matthews *et al*., 2016) was employed as shown in Fig. 4. The mobile application user interfaces are shown in Fig. 5-7 (Table 1). An obstetricians based in any of the developed countries, say United States of America with a pre-assigned authentication code can log in to the SMART system platform to attend to different patients in different parts of the developing countries where the mannequin robot is located. SMART system allows many other specialists/consultants (pediatricians, anesthesiologists, critical care medicine specialists, gynecologists, etc.) to attend to patients in different wards of remote clinics during routine ward rounding.

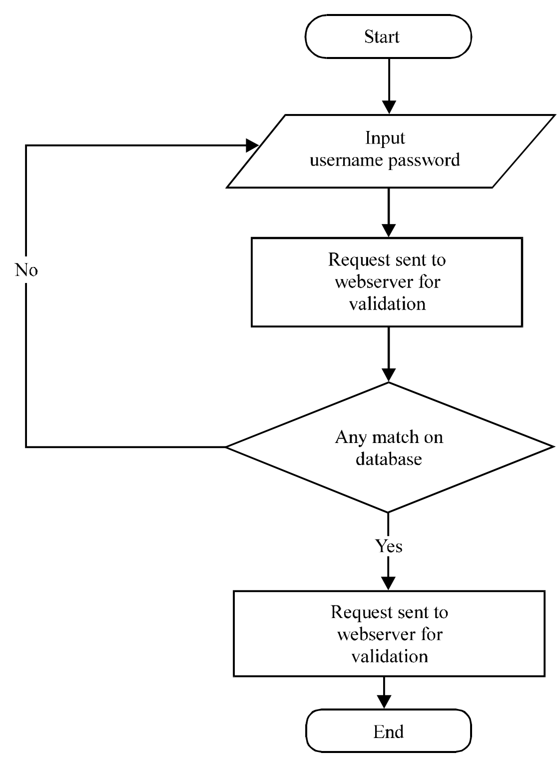

Fig. 6: Web server login algorithm (Matthews *et al*., 2016)

Data signal is transmitted from the smart device or internet-enabled personal computer of the remote medical experts and it is routed through the internet cloud to connect to the SMART system. With a reliable internet connection setup at the rural clinic, the specialist/consultant gains remote control of the SMART system with ease. The movement of the mannequin is guided by the audio-visual information that is clearly available to the user. The user communicates effectively with the assisting community health workers and as well as with the patients through an open-source remote viewer software. This publicly available software is employed to reduce the cost of the overall system.

Table 1: Raspberry Pi 3 specifications

Variables	Explanation
Operating system	Raspbian, ubuntu MATE; snappy ubuntu core, windows 10 IoT core, RISC OS, debian; Arch Linux ARM
System-on-chip	Broadcom BCM2837
CPU	1.2 GHz 64/32-bit quadcore; ARM Cortex-A53
Memory	1 GB LPDDR2 RAM at 900; MHz
Storage	MicroSDHC slot
Graphics	Broadcom video core IV at; higher clock frequencies (300 MHz and 400 MHz) than; previous that run at 250 MHz
Power	800 mA (4.0 W)

Fig. 7: SMART mobile application login page

RESULTS AND DISCUSSION

Component technologies of smart system

Internet protocol network camera: Internet Protocol (IP) network camera is a network-based camera of high definition with the capability to pan, tilt and zoom and transmits data over the Internet. It enables easy access and real time human interactions when the integrated web server is connected to the Internet. There is a high degree of freedom of movement that enables views from different directions and multiple angles. This makes it ideal for continuous object tracking. Users can conveniently zoom in on a farther object for better view. In practice, this type of camera produce irregular response time to control commands, low frame rate, irregular frame rate due to network delays, varying field of view that results from panning, tilting and zooming and different scales of objects. However, with the adaptive fuzzy particle filter algorithm proposed by Varcheie and Bildeau (2011) the displacements in the image plane between 2 consecutive frames is reduced and the detected target location is near to the ground-truth. By this, the camera exhibits a better precision on focus.

A low-cost, energy-efficient IP camera such as shown in Fig. 8 is made up of a video pre-processing unit an H.264 encoder and an embedded streaming server (Yang *et al*., 2009). The video data is acquired and properly formatted by the video pre-processing unit. The output of the pre-processing unit is compressed with H.264 baseline encoding tools and a continuous flow of data is ensured by the streaming server for the Internet video communication. Based on cheap and power efficient blackfin Digital Signal Processor (DSP) and ARM9 processors employed in the encoder and the streaming server and optimal use of the DSP resources, the IP camera delivers Common Intermediate Format (CIF) or Video Graphic Array (VGA) size of real-time video clips directly to the internet with high Peak Signal-to-Noise Ratio (PSNR) quality and low bit rates. This improves video quality at reduced bandwidth and makes the system more reliable.

Mini computer (raspberry Pi): Raspberry Pi, an 85.60×53.98×17 mm single-board computer, performs

Fig. 8: IP network camera

computations with much less power consumption compared to desktop computers, laptops, tablets and smart phones. The low-cost mini-computer has generalpurpose input/output Universal Serial Board (USB) ports (1-4) for connections to external devices. Latest release, Raspberry Pi 3 Model B is equipped with RAM (256 MB-1 GHz), on-board Wireless LAN (Wi-Fi IEEE 802.11n) an 8P8C Ethernet port and Bluetooth. It also features a Central Processing Unit (CPU) with speed range of 700 MHz to 1.2 GHz and a graphic processing unit (GPU). Table 1 provides detailed specifications of the mini-computer. The price of the advanced model varies between US $20-35. The operating system and application programs are stored in Secured Digital (SD) cards of SDHC or micro-SDHC sizes. The system also has a HDMI and composite video output alongside a 3.5 mm audio jack for audiovisual communications.

Figure 9 and 10 show the various components of the mini-computer system. Interestingly, the whole board

Fig. 9: Raspberry Pi model

is powered by a 5-Volt micro-USB power adapter (Upton, 2016). It can be powered using a range of power sources (50) including computer USB port or powered USB hub, special wall warts with USB ports, mobile phone backup battery and solar charger for cell phone.

Wireless communication network: High poverty incidence rate among the rural populations of emerging economies is largely responsible for the current lack of reliable telecommunication infrastructure and services in remote locations of Sub-Saharan Africa. Lack of energy infrastructure, inaccessibility and low revenue potential in the rural areas are major hindrance to the deployment of a functional telecommunication network that is capable of providing reliable broadband internet access (Reigadas *et al*., 2015). Therefore, adaptive low-cost, energy-efficient wireless network technology is required in rural areas of developing countries in order to effectively harness the potentials of ICT in reducing maternal mortality in such areas.

Wireless Fidelity (Wi-Fi) utilizes unlicensed spectrum band to increase broadband internet access which can promote health care service delivery to underserved populations. The use of unlicensed frequency allows hospitals to set up links anywhere anytime as they deem fit, thereby improving sustainability. Large networks can be deployed with IEEE 802.11 after a little changes to the MAC layer. This will enable Wi-Fi transceivers to work

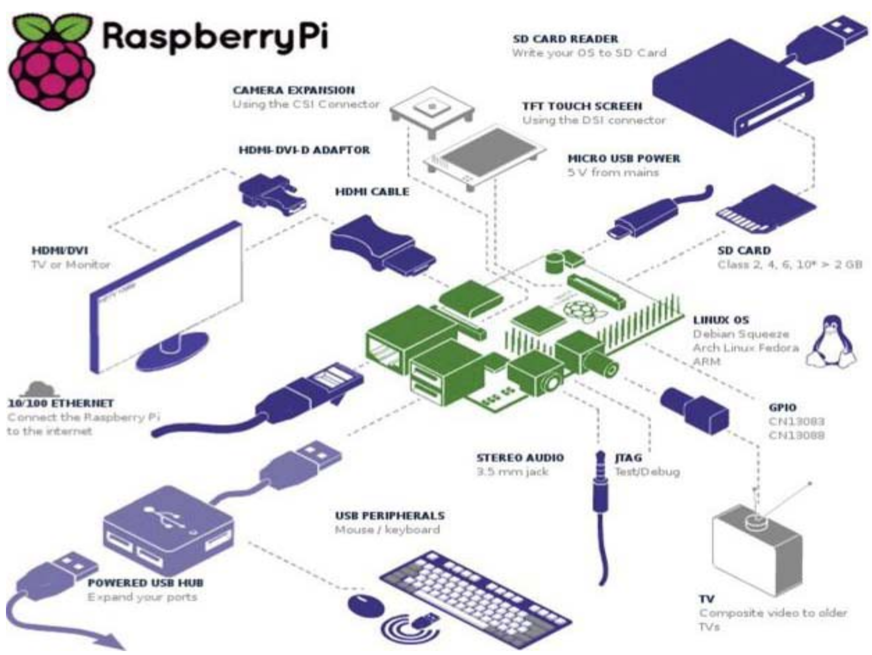

Fig. 10: Components of raspberry Pi 3

effectively especially at very long distances. Costeffective network model adopted has proven the feasibility of the deployment of Wi-Fi over Long Distances (WiLD) and femtocells in achieving broadband internet services in rural areas with acceptable Quality of Service (QoS).

Wi-Fi communication technologies operate at different frequencies to deliver maximum data rates as presented in Table 2. For sustainable Internet services in third world countries, a solar-powered Wi-Fi technology will allows villagers to send signals through an IEEE 802.11 b connection (Santhi and Kumaran, 2006).

Table 2: Wi-Fi technologies

Protocol	Frequency (GHz)	Signal	Maximum data rate
IEEE 802.11	2.4	FHSS/DSSS	2 Mbps
IEEE 802.11a	5	OFDM	54 Mbps
IEEE 802.11b	2.4	HR-DSSS	11 Mbps
IEEE 802.11g	2.4	OFDM	54 Mbps
IEEE 802.11n	2.4/5	OFDM	600 Mbps
IEEE 802.11ac	5	256-QAM	1.3 Gbps

Renewable (alternative) energy generation: Now a days, most of the advanced technologies available to improve way of living are electricity-dependent. Unfortunately, most of the rural areas in the developing world are not connected to the power grid. For instance in Nigeria, the majority of the <40% that are currently connected to the grid are located in the urban centers (UN, 2014). According to United Nation, rural population in Nigeria constitutes approximately 50.4% (UN, 2014). Out of this, only 36% are connected to the grid with not up to fourhour daily supply. In that case, many of the ICT-driven technological solutions have not been efficiently deployed for underserved populations. Whereas rural communities have about 90% renewable energy potentials that are not yet optimally harnessed (Sambo, 2009). The exploitation of alternative sources of energy will aid rapid penetration of ICT-driven technologies for sustainable development in remote locations where accessibility has become a serious challenge.

Solar energy and wind energy options are becoming increasingly popular for low and medium power applications in rural community projects (Dihrab and Sopian, 2010; Hiendro *et al*., 2013). Olatomiwa *et al*. (2016) investigated the potentials of wind and solar energies and the optimal configurations of hybrid renewable system for rural health clinic applications in grid-unconnected rural villages within the selected locations covering the 6-geopolitical zones of Nigeria. The reseacher reported that the hybrid system configurations yielded better results than running on diesel-only with the unique advantage of electrical, fuel consumption and CO_2 reduction.

However, a more recent study by Emetere *et al*. (2016) identified free energy option as a more affordable and efficient means of meeting low and medium power demands in low-income countries. Contrary to general belief, the researcher Emetere *et al*. (2016) proved that the solar energy option is costlier in the long run. In addition, most available PV panels do not last long and the climatic conditions in coastal regions does not support its optimal performance (Emetere and Akinyemi, 2015).

Free (cheap) energy obtained from either thermodynamics or magnetic field will have no adverse effect on the planet. In order to guarantee both availability and affordability of energy in the remote locations of developing countries, SMART is also designed to operate on free energy generators 4.

Table 3 shows the prices of available robotic telepresence systems in the market and that of the developed SMART system. The results showed that

Table 3: Comparative cost analysis

Product name	Figs	Manufacturer	Price
Beam+smart; presence system		Suitable technologies (https://suitabletech.com/beam pro)	$1,995.00
Double 2; telepresence robot		Double robotics (http://www.doublerobotics.co m)	$2,499.00
Kubi telepresence robot		Kubi (https://www.kubi.me)	$1,907.00

Table 3: Continue

Product name	Figs	Manufacturer	Price
Vgo robotic; telepresence system		VGo communications (http://www.vgocom.com)	$5,995.00
AMY robotic; telepresence		AMY robotics (http://www.amyrobotics.com)	$6,999.00
SMART system		Embedded and telecommunications; Lab, Department of Electrical and Information engineering; Covenant University, Ota, Nigeria; (www.covenantuniversity.edu.ng)	$456.00

SMART is more affordable with better efficiency. Therefore, low-income countries can exploit the huge potential of this system to address serious challenges facing the healthcare sector in the region.

CONCLUSION

Considering the high level of extreme poverty in Sub-Saharan Africa and the unreliable power grid in this region, most of the available mobile robotic telepresence becomes relatively unaffordable for deployment in the rural communities. However, plastic mannequin telepresence which utilizes two IP network cameras with ability to communicate over the internet using Wi-Fi transceiver module available on Raspberry Pi successfully minimize cost and does not rely on the mostly unavailable conventional power from the grid. The system was designed to operate on solar PV system or free energy alternative source to ensure availability of required electrical power at low cost. Following a proper authentication process, a medical consultant based in any of the developed countries can easily log in to the SMART system platform and attend to patients in different parts of the developing countries where the mannequin robot is situated. SMART system allows other specialists/consultants (pediatricians, anesthesiologists, critical care medicine specialists, gynecologists, etc.) to guide community health workers in better health care delivery to rural populace during routine ward rounding. Patients seems to be more comfortable with a real human during treatment rather than a machine. In clear departure from the norm this system gives a better impression of the physical presence of a medical specialist than existing mobile robotic telepresence which are not purposely designed to particularly fulfil that purpose. Compared to existing telepresence robot which are too expensive and not sustainable in emerging economies, SMART system is a cost-effective, energy-efficient and ecofriendly solution that has an enormous potential to significantly reduce maternal mortality in Sub-Saharan Africa.

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