Simulation of Photovoltaics for Defence Applications

Power Generation Assessment and Investigation of the Available Integration Areas of Photovoltaic Devices on a Virtual Infantryman

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Abstract: The use of photovoltaic (PV) technology for the harvesting of renewable energy is a reality and is widely employed today. However this is mainly focused towards house and industry energy harvesting. Recent development in thin and flexible materials mean that photovoltaic technology can be integrated into wearable computing and expanded to other commercial as well as defence applications. This paper presents work under the Solar Soldier project that aims to assess the incorporation of flexible PV technology on the modern infantry soldier through the modelling and simulation of virtual military scenarios. The scenarios consist of various military operational terrains, various lighting conditions as well as motions of the virtual infantry soldier. The scenarios are simulated in a systematic way and for numerous global positions of military interest. The results of these simulations are then organised and presented in a manner leading to the assessment of the power generation potential per scenario and investigation of the optimum integration areas of flexible PV devices on the infantryman.

1 INTRODUCTION

Despite the modern advances in military technology the infantry soldier continues to play a very significant role in defence. In the age of stealth jets, nuclear munitions and guided weapons, it is still the infantry soldier that examines and secures a location to ascertain whether the target area is cleared and the enemy is defeated. The modern infantry soldier utilises the electronic technology and resources available today, in order to penetrate into hostile and difficult terrain where armoured vehicles cannot trespass and overcome the enemy. The power requirements of such electronic technology, critically essential for the modern soldier, are much higher when compared to the power requirements of a civilian counterpart. Furthermore, the environment of operation is far more hostile and challenging than those of the civilian applications and the loss of power may endanger the infantry soldier's life. That is the main reason behind the massive overload of batteries constituting the 25% (source Ministry of Defence of United Kingdom, MoD of UK) of the overall equipment load (including lethal, survival and communication). This fact indicates that there is an uncontested restriction of manoeuvrability, operational range and a significant physical and cognitive burden.

The recent advances in the field of sustainable energy and particularly the innovative flexible and wearable photovoltaic (PV) technologies could offer a potential solution to this issue, by removing, or reducing at a great extent, the use of batteries. The Solar Soldier project, which is partly funded by the Defence Science and Technology Laboratory (DSTL) of the MoD of UK and the Engineering and Physical Sciences Research Council (EPSRC), investigates this research challenge. Part of this project is the work presented by this article which focuses on how one could integrate the PV technology epitomising the Solar Soldier concept from a human interface and design perspective. The objectives of this challenge are twofold:

- To assess the incorporation of the PV technology on the uniform and equipment of the infantry soldier.
- To measure and evaluate the effectiveness of each area (amount of power generated under various scenarios) as well as to investigate the areas that yield the same power values all over

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their extent for further research on usability (human comfort, intuitiveness).

The bounds of this paper include and present the study of the second objective with a focus on the effectiveness of the proposed system. The usability of the device is examined by liaising and interacting with the Infantry Trials and Development Unit (ITDU) of the DSTL in order to acquire more in depth knowledge on the casualties and motional habits of infantrymen during military operations. The effectiveness of the device is measured by employing the use of Virtual Simulations.

The article is organised in a number of sections including an introduction and theoretical background, presentation of the adopted methodology, the results section, the discussion and guidelines that are inferred by the results and finally the conclusion.

2 BACKGROUND

The theoretical background of the study presented in this paper belongs in various research areas such as modelling and simulation (M&S), virtual reality (VR) applications and product design aspects.

2.1 Virtual Reality and Defence Applications

The advances of VR, in recent years, have led to the development of new areas of applications beyond the entertainment industry. Research and development in interactive VR has been employed in the areas of training, education, health and simulation with one of the major areas of interest being military and defence applications (Zyda, 2005). VR can be utilised for military applications to perform a wide range of simulations. These range from cognitive and behaviour simulations in battle to ergonomic simulations; all serving the improvement of the welfare of the modern soldier. These simulations have to be conducted in a virtual framework often consisting of assets that offer 3D graphical representations of terrains, human avatars and objects as well as weather and daylight augmented systems. All these elements create a Virtual World on a computer-based simulated environment. This is of significant interest and importance to research, as it offers a very useful alternative reality especially for situations, such as ours where actual experiments are not feasible or dangerous to conduct in real life (Jarvenpaa, Leidner, Teigland, and Wasko, 2007) (Chaturvedi, Dolk, Drnevich, 2011). More precisely, Reece (2003) has studied the movement behaviour of soldier agents on a virtual battlefield, the Santos Project (Abdel-Malek, Yang, Kim, Marler, Beck, Swan, Frey-Law, Mathai, Murphy, Rahmatallah and Arora 2007) (Yang, Rahmatalla, Marler, Adbel-Malek and Harrison 2007) offers a virtual platform for human ergonomics in military environments and Shiau and Liang (2007) present a real-time network VR military simulation system comprising weather, physics and network communications. Blount, Ringleb, Tolk, Bailey and Onate (2011) have introduced the aspect of physical fitness into simulations for infantry soldiers and others such as Cioppa, Lucas and Sanchez (2004) and Bitinas, Henscheid and Truong (2003) have worked with agent-based simulations and their military applications, focusing on human factors in military combat and non-combat situations respectively. The aforementioned literature focuses mainly on simulating human factors and ergonomics either in the production line or in military environments. However the applications of VR Human Centred simulations are not restricted to ergonomics. The aspect of Human Centred Design (HCD) that this article examines is the integration of renewable energy devices on the human vesture and in particular the integration of PV on the uniform and equipment of the modern infantry soldier in terms of light capture efficiency.

2.2 Simulation of Solar Light Harvesting and Power Generation Estimate

Currently the main focus of PV technology and its corresponding simulations has been on building and infrastructure applications. The very recent developments in the area of PV devices **(**Parida, Iniyan, Goicm, 2011), (Chaar, Lamont, Zein, 2011) along with the introduction of thin films and flexible materials for light absorption (Hashmi, Miettunen, Peltola, Halme, Asghar, Aitola, Toivola and Lund, 2011) have attracted the focus of harvesting renewable energy to human centred applications as well. The study of the performance of the so-called Product Integrated PhotoVoltaics (PIPV) (Reich NH, van Sark, Turkenburg and Sinke, 2010) is twofold. Firstly, to investigate the performance and electrical characteristics of the PV device itself; secondly to study the effectiveness of light harvesting and power generation, which is also the main focus and aim of our work. The effectiveness of power generation depends on the interaction of the device with the environment as well as on the type of integration of the PV on the product (e.g. attached on clothing, embroidered or woven onto the fabric). The environmental conditions would require the modelling of daylight and shading in a 3D authoring and simulation tool, whilst the integration guidelines would require simulated scenarios and results that would infer the most effective method of integration.

2.2.1 Daylight and Shading Modelling

With regards to daylight modelling there have been numerous studies on methods to maximise solar system outputs such as the work of Mousazadeh, Keyhani, Javadi, Mobli, Abrinia and Sharifi (2009). Apart from research studies there has been major development in the corresponding software industry with very intelligent and complex packages developed for daylight simulations, including 3D Studio Max Design by Autodesk (3DSMD), which is the software utilised in this project. 3DSMD was chosen mainly because it comprises a toolset for animation and because it includes the feature of light analysis of a 3D scene, which is essential for a HCD project such as this. 3DSMD also offers extension capabilities through its embedded programming language, Maxscript. It can thus be used to semi-automate the procedures as described in the work of Paraskevopoulos and Tsekleves (2011). The results of the light analysis of 3DSMD have been validated by Reinhart and Breton (2009) and Paraskevopoulos and Tsekleves (2011) and the software has been used in a number of other studies regarding light harvesting for PV (Reich et al, 2010), (Reinders, 2007). Nevertheless, all of them have focused on simulations where the PIPV device was in a static position and none of these has studied the effect of light analysis simulation whilst the PIPV is on the move. Furthermore no previous work has offered any conclusions or guidelines on the design aspects of wearable PVs in terms of power generation efficiency. Power values are calculated using the simulated light intensity values and for areas spread as much as the value is relatively constant. The extents of these areas provide an area estimate and design guideline to the PIPV designer.

2.2.2 Integration of PV on Commercial Products

Although the integration of PV on commercial products is not a new idea, the emergence of flexible and thin film materials has extended the possibilities of integration into more products with a smaller scale factor which can be portable. However, until recently and as stated in the work of Mestre and Diehl (2005) there have been no guidelines for the integration of PV on products in the context of either human comfort or efficiency of energy harvesting. The work of Reinders (2002) examines in depth the options for PV systems and portable devices and presents their advantages and drawbacks. Among the drawbacks one indicates the lack of PV technology penetration in our society and market. This is mainly due to limited knowledge of this technology by product designers and manufacturers, restricting in turn the extension of applications for this technology. Our work presented in this article aims to fill in this gap by deploying design guidelines and a simulation platform on the integration of PV on military garment and equipment initially and commercial products in the future. As already mentioned in the introduction of this article the use of virtual reality simulations is a prerequisite for military applications due to the hostile and extremely hazardous environment. Randall, Bharatula, Perera, Von Buren, Ossevoort and Troster (2004) have integrated solar modules to use them as light sensors in order to collect physical measurements and not for the purposes of light analysis simulation. With regards to the design aspects of the integration of PV on clothing Schubert and Werner (2006) have presented an overview of flexible solar cell technologies applied on wearable renewable sources. This however focuses only on the material aspect of PV. In their paper Schubert and Werner (2006) reference Gemmer, who has performed experimental investigation on light harvesting under different daylight scenarios and has calculated energy yield for various user profiles, for example a “regular clerk”, an “outdoor construction worker” and a “night shift nurse”. In the system we propose these profiles can be very easily modelled (3D avatars and motion capture) and simulated (light analysis tool, 3DSMD) for all various light conditions (daylight system, 3DSMD) and encompassing environments (3D terrain models). The outcomes of such simulations would infer the design guidelines of the most efficient manner of integration of PV on clothing in terms of light harvest and power generation.

3 METHODOLOGY

The problem stated in the Introduction of this paper requires the employment of a virtual framework able to conduct a number of experiments and collect measurements, which are impossible to collect due to the hazardous nature of the real environment. The methodology that fulfils the development of such a virtual framework is Modelling and Simulation (M&S). The application of M&S presented in this article is aimed at applying an existing feature of a 3D authoring commercial software, 3D Studio Max Design (3DSMD), by extending its capabilities and applying it to simulation of daylight for sustainable energy applications of military interest. The lighting analysis system of 3DSMD will be employed in a virtual military environment framework. The light sensors are employed as design assets by the software and attached on specific areas of the soldier's uniform and equipment to assess the incorporation of PV technology. The Block Diagram of Figure 1 illustrates the overall adopted methodology. The initial step of the methodology is to acquire all virtual assets required for the scope of the modelling and then manipulate them together in the 3D assets Manipulation stage. The 3D asset manipulation stage includes a human avatar (British army infantry soldier), a set of animation clips (motion capture) and virtual terrains (forest, urban area, military camp). These have to be manipulated (modelling, scaling, texturing, animating) in order to fulfil the requirements of the planned simulation scenarios. Then all the assets are merged together. The 3DSMD daylight system is set up and the light sensors are designed. This completes the virtual scenes ready for simulation. The simulations yield raw data in Comma Separated Value (CSV) form, which then can be easily transformed to spreadsheets and imported to Matlab for further analysis and presentation.

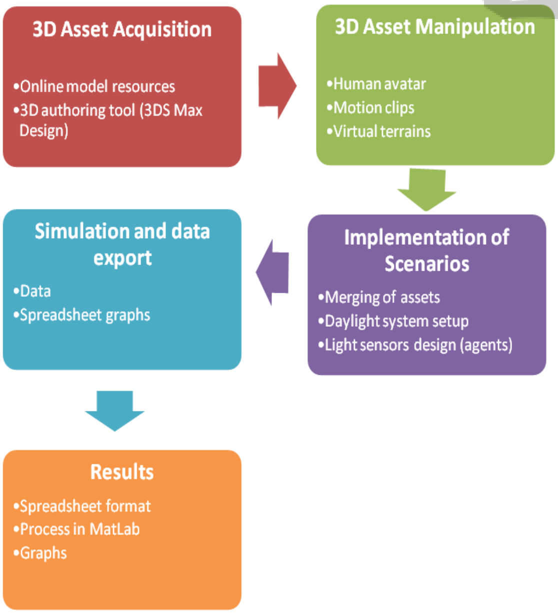

Figure 1: Block diagram of the overall methodology.

3.1 Modelling

This stage includes the 3D asset acquisition and manipulation as illustrated in the block diagram of the overall methodology (Figure 1). The final outcome of the modelling process is a virtual framework that includes a series of military scenarios, which are comprised of a virtual military terrain, a human avatar (virtual infantry soldier) and a range of movements. All various assets, either designed or acquired from online available sources, are then manipulated by incorporating them together in unique scenes along with the daylight system and the other assets (virtual light sensors and animation clips). Further additional amendments are performed on the models to ensure compliance with the requirements of the lighting analysis plug-in of 3DSMD with are presented in the Daylight Simulation tutorials by Autodesk (2009) and also discussed in the work of Paraskevopoulos and Tsekleves (2011). These amendments include adjustments of the lighting system, modification of the materials and lighting analysis render setup. Among the aforementioned modifications, the lighting system setup is the most significant as in this setup we configure all the important parameters of our daylight system. For example, the date and time, the global locations as well as the sky model are configured in this setup. Most significantly though, the input of the system, in terms of light intensity, is adjusted through the lighting system setup, which is the daylight system available in 3DMSD and its corresponding modification panel. For the purposes of this study we employ, as our system input, the irradiance data provided by Photovoltaic Geographical Information System (PVGIS) (Sŭri, 2007). PVGIS is an online system developed by the Joint Research centre for Energy and Renewable Energy Units. The embedded light analysis tool of 3DSMD does not incorporate a feature for analysing mobile light sensors as the main application of light analysis is in the area of building engineering. For that reason, we developed a script to perform an analysis for virtual scenes containing mobile objects such as the human avatar, in our case. The script exports light data with a sample rate that the user can choose. For instance for an animation with a default frame rate of 30 frames per second (fps) and a total of 3000 frames (1 minute and 40 seconds), the user can set the sample rate of analysis to 1 second. In this case the analysed frames will be every 30 frames resulting to 100 measurements. The measurements are then exported by the same script to spreadsheet format and imported to Matlab for further analysis. Therefore, in our approach we utilise a commercially available 3D authoring tool and extend it by using its own programming interface and employ an M&S methodology to an application of military interest. This methodology enables our study to be the first one to analyse mobile light sensors in a virtual environment.

3.2 Simulation

After the modelling of the environment and merging with the other virtual elements, the simulation procedure is enabled. Apart from the 3D models, every scene comprises virtual light sensors attached on various areas of the soldier's uniform. The distribution and positioning of the sensors on the uniform are based on suggestions and recommendations after liaising with the corresponding expert of DSTL and computational power restrictions (the number of sensors is typically 8 for most high end computers) Figure 2 and Figure 3 depict the positioning of the selected sensors on the soldier's uniform and helmet:

Figure 2: Distribution of sensors (front view).

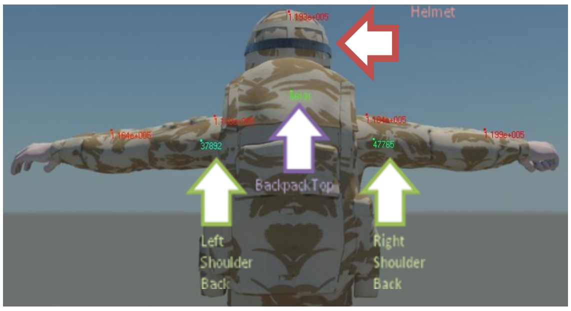

Figure 3: Distribution of sensors (back view).

Eight light sensors comprise the collection of sensors, namely:

Table 1: List of light sensors.

Right Shoulder Middle	Left Shoulder Middle
Right Shoulder Back	Left Shoulder Back
Right Forearm	Left Forearm
Helmet	Backpack Top

These sensors are attached on the geometry of the human avatar, thus they follow every movement their parent geometry performs. Several 3D models have been employed for the purposes of our simulation. These can be listed as follows:

Table 2: 3D models collection.

Terrain	Forest Scene
	Military base
	Urban area
Human Model	Infantry soldier (Royal Anglian model)

The 3DSMD Daylight System is employed as the lighting system, which is global position adjustable. After the design of the solar system the scene is ready to be animated. For the purposes of this study, the animation clips selected were that of a walk-cycle that is one of the most typical motions that a dismounted infantry soldier performs on average in most missions. The global locations to examine are also limitless. Since the work conducted is part of a military project of the British Royal Army, a few locations of interest for the purposes of the project were selected.

Figure 4: Major British Troops Deployments (Source: British Broadcasting Corporation).

Figure 4 illustrates the major deployments of British soldiers around the world. The choice of locations to examine covers various latitude and longitude ranges. Thus, the following strategic points of interest are chosen, which offer distinct locations in terms of both longitude and latitude:

- U.K., Catterick Garrison, (54.375, -1.708)
- Kosovo, Pristina (42.5, 20.9)
- Iraq, Baghdad (33.33, 44.44)

The resulted scenes must be simulated in such a manner that they would cover a wide range of times and dates. The range of times would have to cover most of the effective time in the day in terms of lighting; that is some hours before and some hours after midday. The dates would have to cover all seasons. Therefore, the proposed dates and times under examination are shown in Table 3.

Table 3: Times and Dates.

Times	10.00
	12.00
	14.00
	16.00
Date	Winter (07 Jan)
	Spring (16Apr)
	Summer (08Jul)
	Autumn (26Oct)

The times selected are only in daylight time and not during darkness for the following reason. This article is part of the work conducted for the Solar Soldier project, a consortium of 6 Universities all of which investigated a specific aspect of the incorporation, storage and distribution of electrical power produced by coupled photovoltaic and thermoelectric elements. The problem of energy production during the times of no or very low light is tackled by the use of supercapacitors for storage as well as the use of the thermoelectric device.

The dates themselves are random but the months are one every four and each from a different season. The light data required for the input of our virtual light system are taken from the PVGIS project as mentioned above. It covers only the European and Africa continents, which fits within the requirements of this study. The online calculator provides the user with monthly average solar irradiance values for a given slope. The irradiance data is measured according to the international system with watt per square meter (W/m^2). The software uses illuminance values which are expressed in lumens per square meter (lm/m^2) or lux. The conversion of W/m^2 to lm/m^2 is a very complicated and circuitous mathematical procedure that requires the engineer to know the spectral composition of the source in order to solve the conversion formula. A publication in the scientific disciple of horticulture, conducted by Thimijan and Heins (1983) provides a table with measured and solved conversion factors for different sources including the sun for various spectrum portions. Thus, the interconversion of radiometric to photometric units enables the simulation with typical monthly average irradiance values as input. The simulations infer light level estimates of the given sensor setup for each of the scenarios generated and according to the adjustment of the various parameters described above. The total scenarios generated and simulated are 144 each one containing 8 light sensors. Each unique scenario differs in time, date, global location and terrain type.

The differences of each terrain development imply various walking distance and angles, although a general rule was followed; to animate a walk route of a block in order to cover all orientations (north, south, east and west).

The frame rate for the animation was the default value of 30 frames per second. For reasons of computational economy, the sample rate of the light analysis script described above was set to 2sec. With all these conditions every simulation cycle lasted about 1hour. Therefore, for the examined scenarios the authors required about 144 computing hours on a desktop PC with an i5 processor and 4 GB RAM.

The resulting average light level values for each scenarios and for each unique sensor is transformed back to W/m^2 and along with the guidelines from DSTL liaising we calculate the optimum areas of integration for each PV device on the soldier as well as the average power values that they yield for each of the examined scenarios. The results are organised and stratified in increasing order so that a general guideline is established and can be used for future reference by PIPV designers and practioners. In order to accomplish that, we utilise MatLab and its data manipulation and graphical plotting toolsets. MatLab was chosen for its high performance and automation features that simplify the manipulation of such massive sets of data.

For the power output levels, we used the illuminance results of the simulations to calculate the extent of the area on which this illuminance value of each sensor is not significantly altered. Therefore, hitherto sensor is replaced by the concept of an area on which the light harvesting is almost invariable. The extent of this area describes a unique area of integration. Using the value of the area and the efficiency value (5%) of the prototype PV device developed for the Solar Soldier project by our partners from Loughborough University we are able to calculate and produce the average power graphs of each sensor (in watt) using Matlab.

4 RESULTS

As described in the previous chapters, the aim of this study is to simulate the use of PIPV technology in different military environments and under various lighting conditions and to investigate the optimum integration of this technology on the uniform and equipment of the modern infantry soldier. The results of the simulations will manifest the stratification of the various candidate areas of integration on the uniform and equipment in the context of higher power yield. These results can be used by engineers and PIPV designers as a draft blueprint of how and where to incorporate the PV devices on the infantry soldier according to each scenario. The results are organised in graphs of the power yield for each season and under all scenarios are presented. The average power values in W for each of the scenarios and for all areas are organised and presented in figures 5-13 in the Appendix. Afterwards, the results are interpreted and the classification of the areas can be inferred by comparing the values of each season. Table 4 provides the overall classification in terms of power generation for the examined scenarios as well as the extent of each area in cm^2:

Table 4: Integration areas classification.

Scene	Area Classification	
Forest	1. **Backpack**	300cm^2
	2. Helmet	314cm^2
	3. Forearms	100cm^2
	4. Shoulder Mdl	70cm^2
	5. Shoulder Back	60cm^2
Military Base	1. **Helmet**	
	2. Backpack	
	3. Forearms	
	4. Shoulder Middle	
	5. Shoulder Back	
Urban Area	1. **Helmet**	
	2. Backpack	
	3. Forearms	
	4. Shoulder Middle	
	5. Shoulder Back	

5 DISCUSSION & GUIDELINES

As stated in the Introduction, the usability of the PV device proposed by the Solar Soldier project is examined by liaising and interacting with DSTL. This interaction derived to a preliminary set of guidelines for the integration of PV on the uniform or equipment. The feedback we received from DSTL enabled us to narrow down the potential areas where PIPV could be integrated and thus reduced the number of light sensors to use in our simulations. For instance, it was gathered that the chest and the back of the uniform areas would not constitute good candidate areas for installation of PIPVs as they are constantly occluded by the gun and hands holding it and by the backpack respectively. The second set of guidelines derived from the case studies of the three different environments presented above. Table 4 provides a draft guideline for designers and manufactures of wearable PV devices in military environments. It is clearly shown that this classification can provide guides for the positioning of such devices on the uniform and equipment of the infantry soldier for the examined areas. For instance, the helmet would be the first choice for every case and environment. This fact was more or less predictable yet not validated by any study so far. Moving on, we notice that the top of the backpack as well as the forearms as a set (right and left) qualify as important area candidates for integration. The rest areas qualify only as supplementary areas as they show poor performance and come low in most classifications. Combining the simulation data presented in this paper along with the feedback on the HCD ascertained from DSTLwe can provide the following set of guidelines and recommendations with regards to the integration of PIPVs on the modern infantry soldier:

1. The best places on the soldier’s uniform in terms of ergonomics and power generation are the helmet followed by the backpack and forearms. These three positions will provide the PV system with constant exposure to solar radiation, which can be converted to energy even when the soldier is on the move.
2. It is recommended that the entire backpack is covered with PVs as, on one hand, more PV panels can be placed and thus more energy can be harvested at all times as the soldier can easily leave the backpack in the sun whilst resting. Although the helmet yields the highest amount of light its consistent supply of power to the solar harvesting system may be stopped in certain cases. In very warm environments of operations the soldier will seek shade under natural and man-made constructions such as trees and buildings and may even take off the helmet whilst resting. This necessitates further the need to place PVs on the backpack as it can be removed and placed under the sun.

3. Integrating PV directly into the uniform is not recommended as this is washed in extremely boiling hot water. As fabric and nano-material technology evolves it may be able to interweave the solar panel nano-material onto the uniform that will withstand extremely high temperatures. Until then it is recommended that the solar panels are attached onto Velcros so that the PV can be attached and detached. This would also enable the interchange of the PV positioning on the uniform according to the environment and location of operation

6 CONCLUSIONS

Infantry soldiers today carry around a lot of electronic equipment which have high power consumption requirements. This forces them to carry, in dismounted operations, several heavy and bulky batteries which increase dramatically their total equipment load. Renewable energy technology such as the incorporation of PVs can substitute batteries and relieve the soldier from the physical and cognitive load. This study has proposed a virtual simulation framework that mimics closely the military environment for the purposes of investigating the integration of PIPV technology on the infantry soldier, by analysing and measuring the effectiveness of light capture on various areas of the uniform and equipment of the soldier. The examined case studies covered several basic military environments as well as the several potential areas of integration of the PV device after interacting with the army. After performing the simulations, the resulting data were organised and presented in such a manner enabling the classification of the examined areas in order of power generation efficiency. The derived overall classification infers draft yet qualitative guidelines for any designer or practitioner of wearable military applications.

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APPENDIX

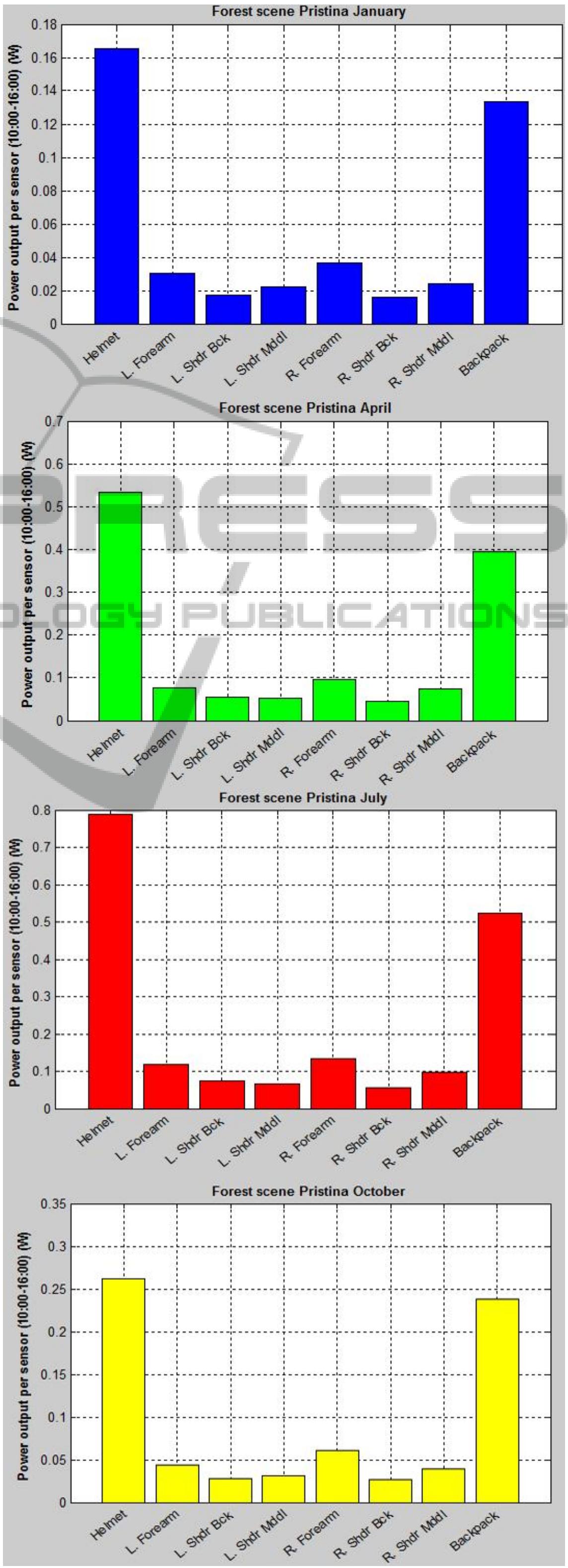

Figure 5: A Forest scene in Baghdad.

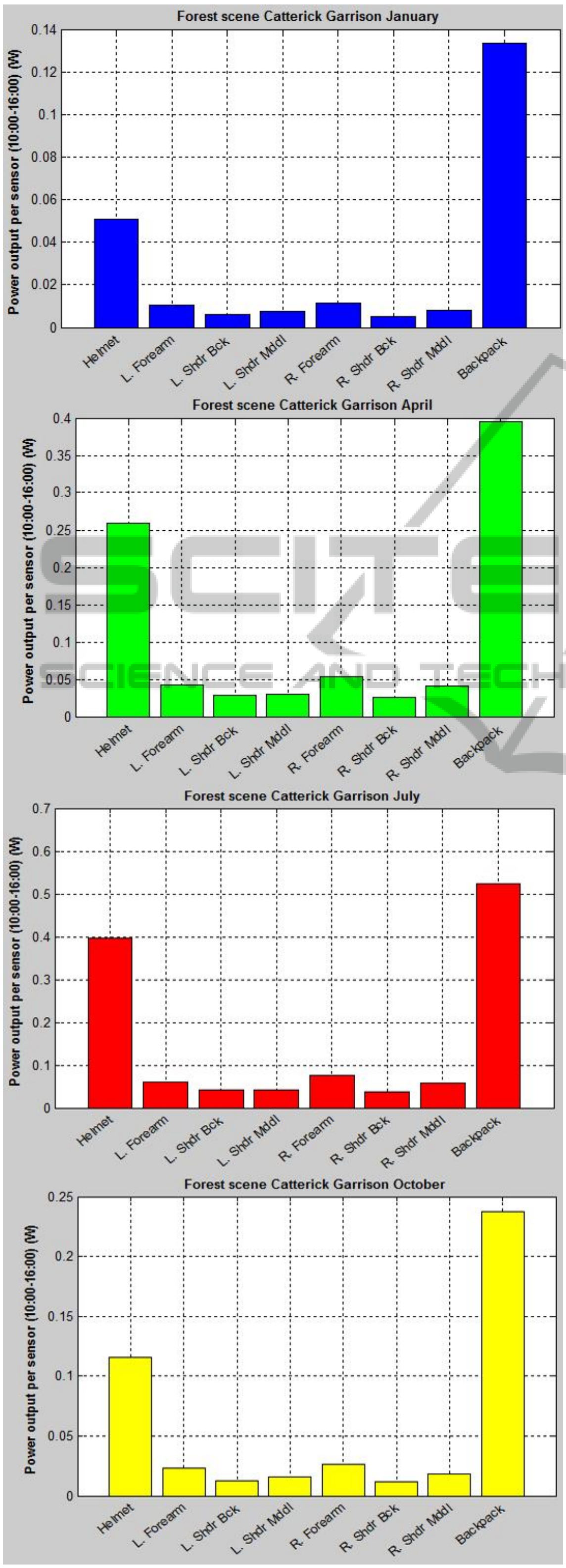

Figure 6: A Forest scene in Catterick Garrison.

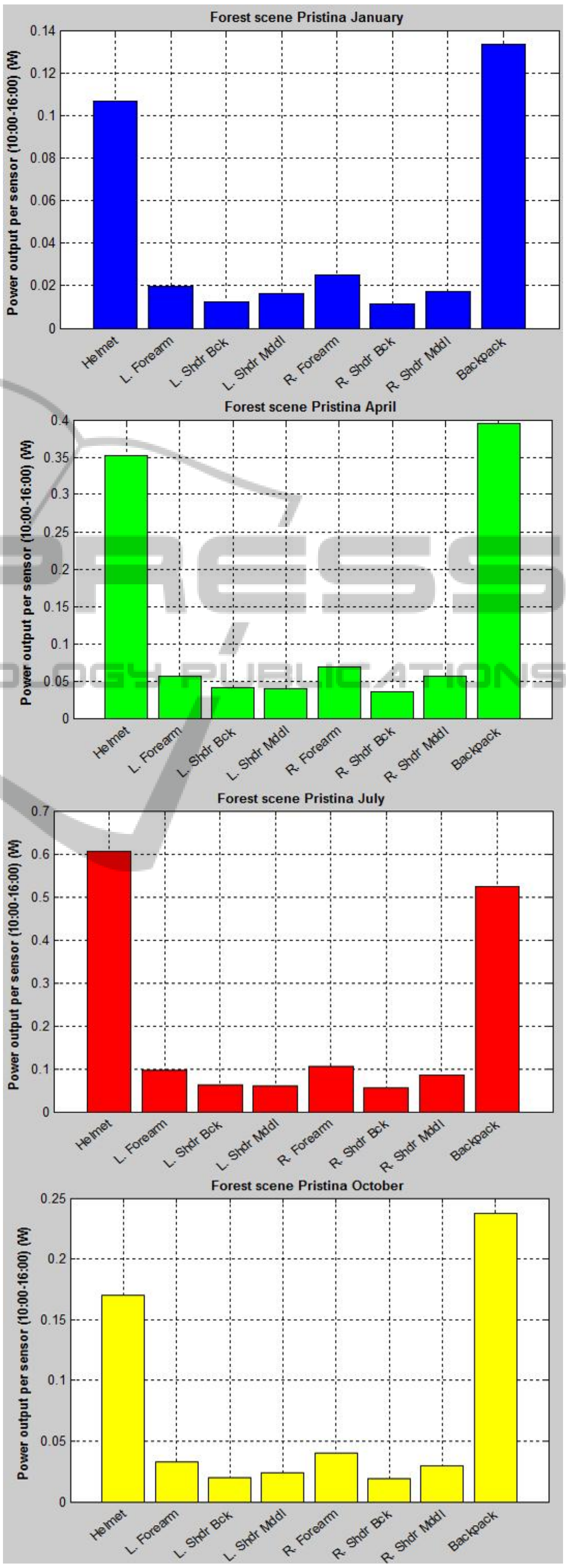

Figure 7: A Forest scene in Pristina.

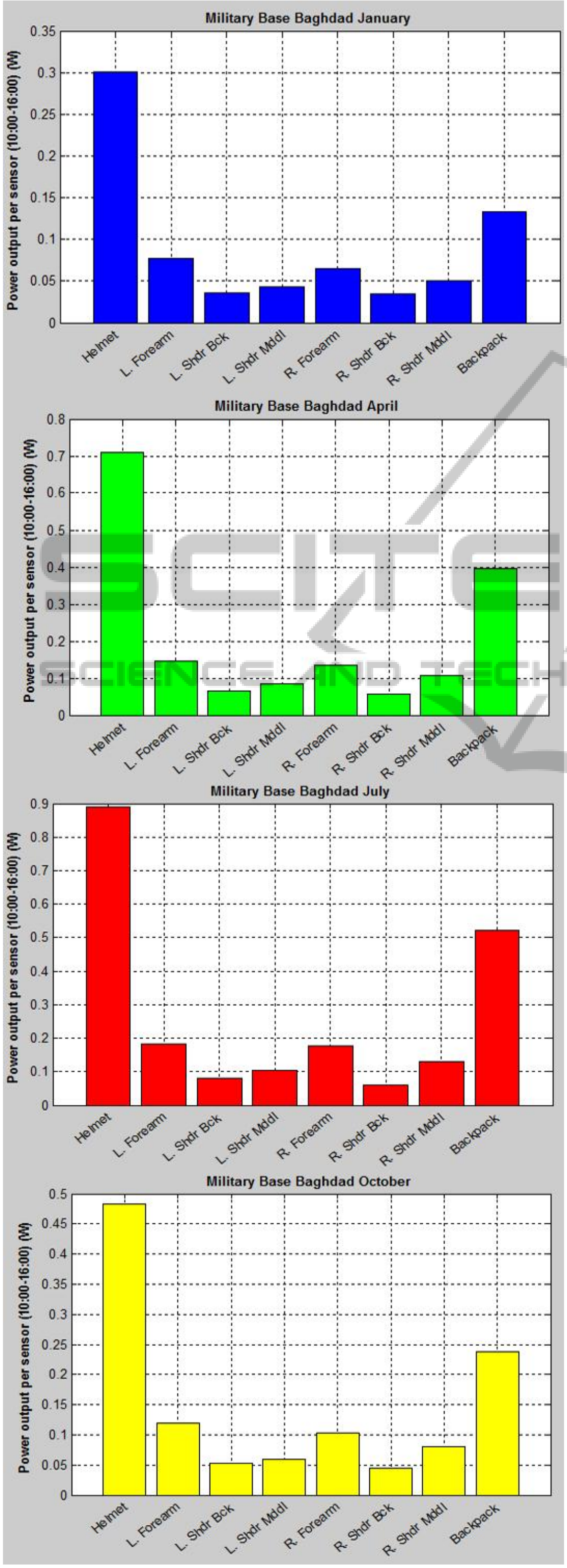

Figure 8: A Military base scene in Baghdad.

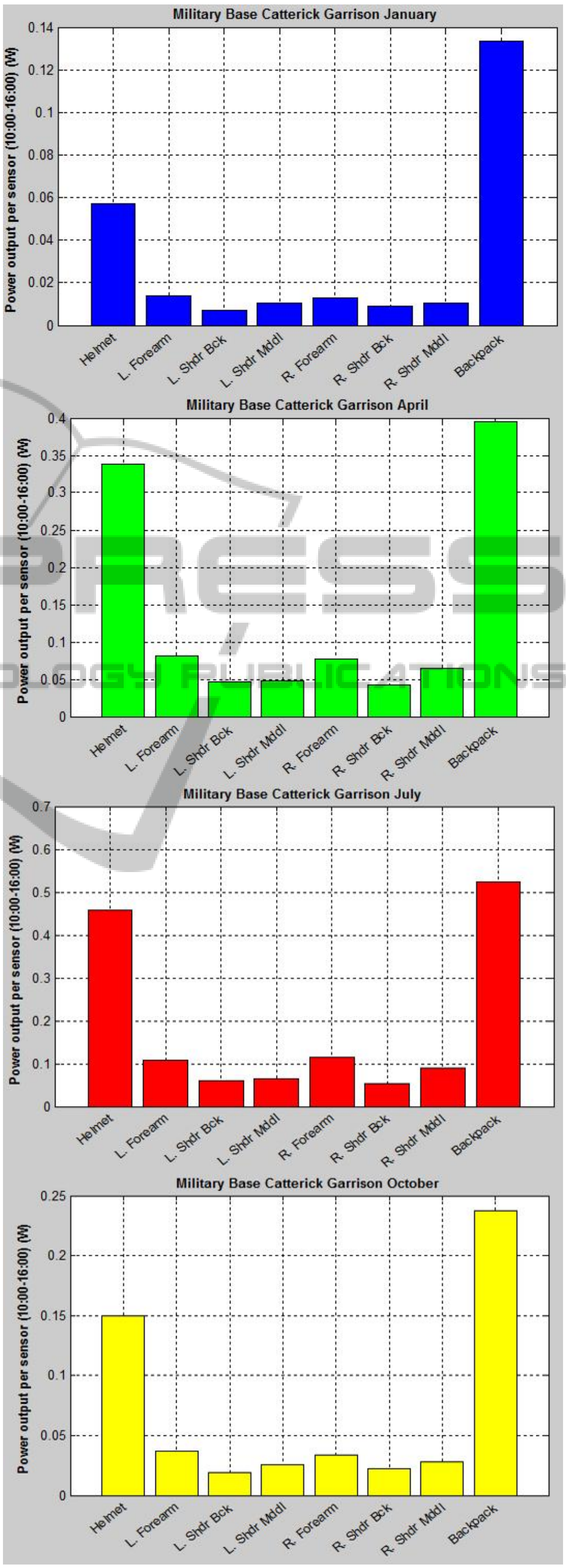

Figure 9: A Military base scene in Catterick Garrisonb.

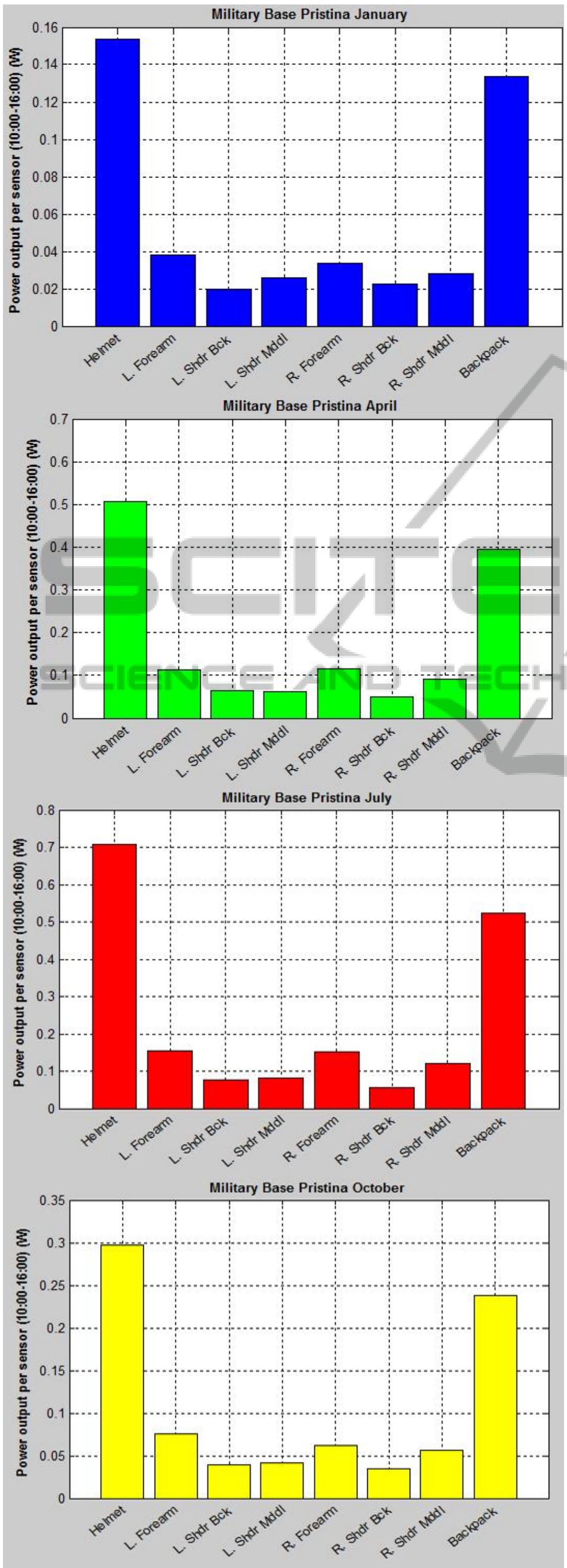

Figure 10: A Military base scene in Pristina.

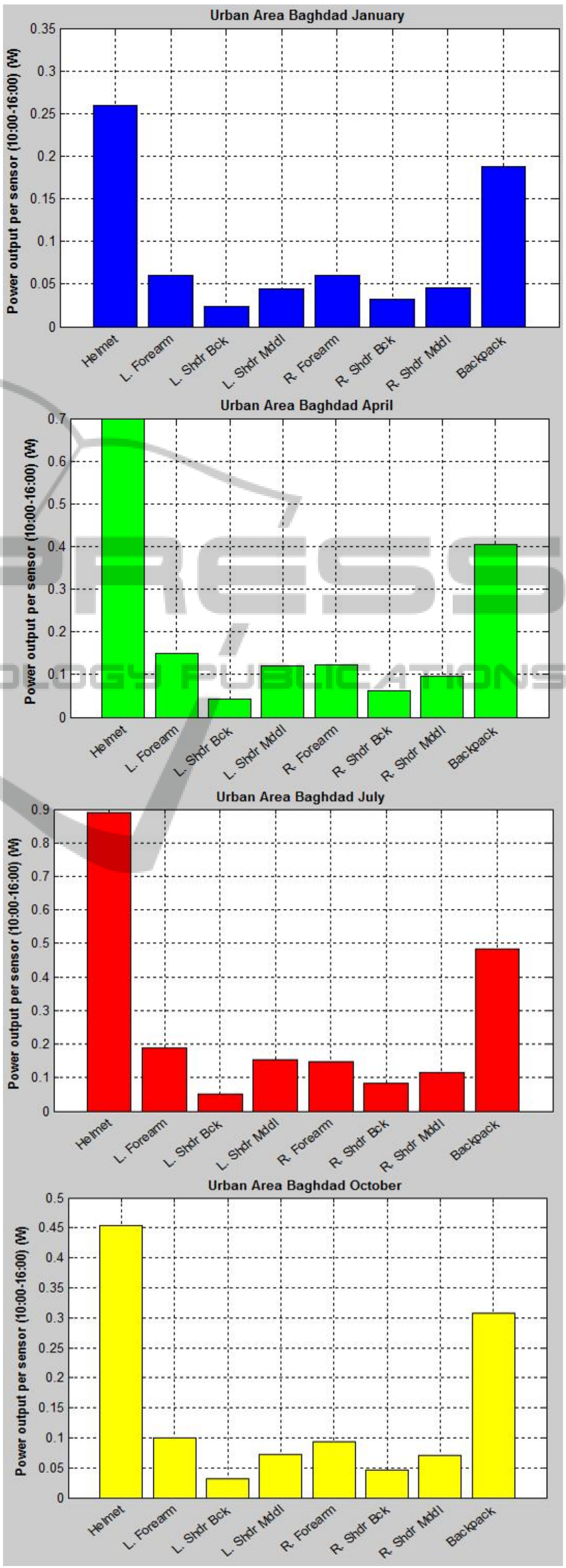

Figure 11: A Urban area scene in Baghdad.

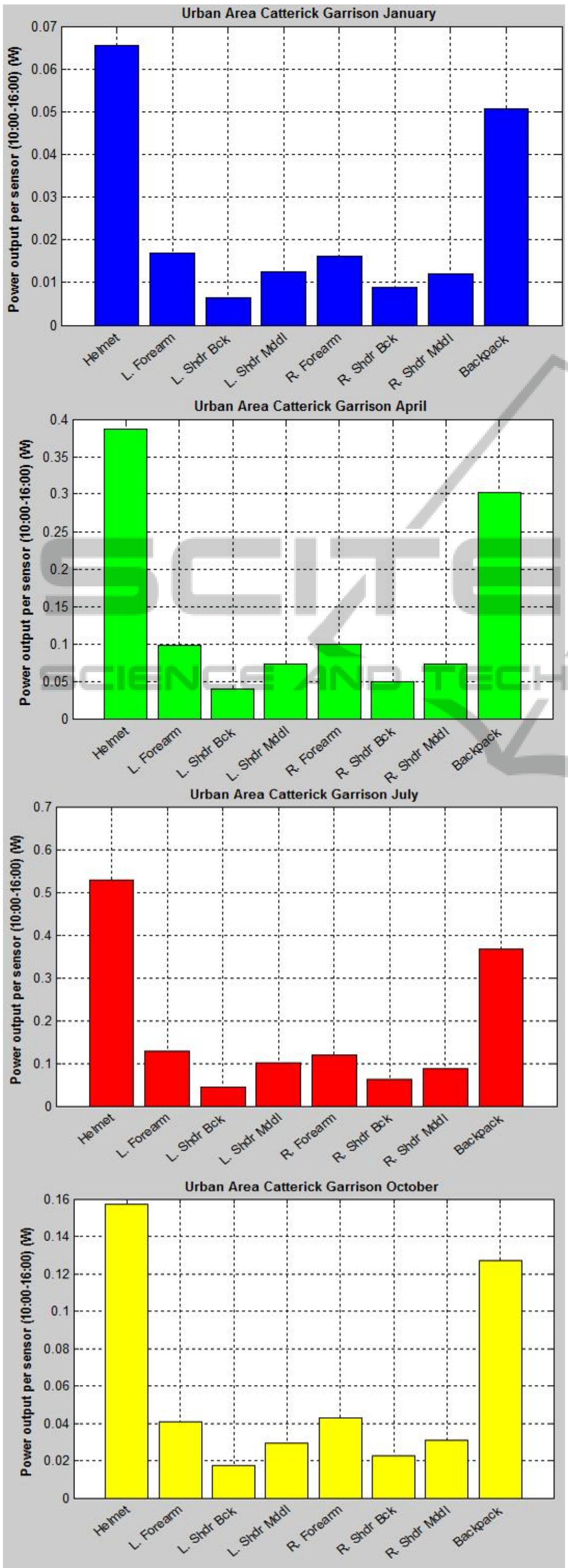

Figure 12: A Urban area scene in Baghdad.

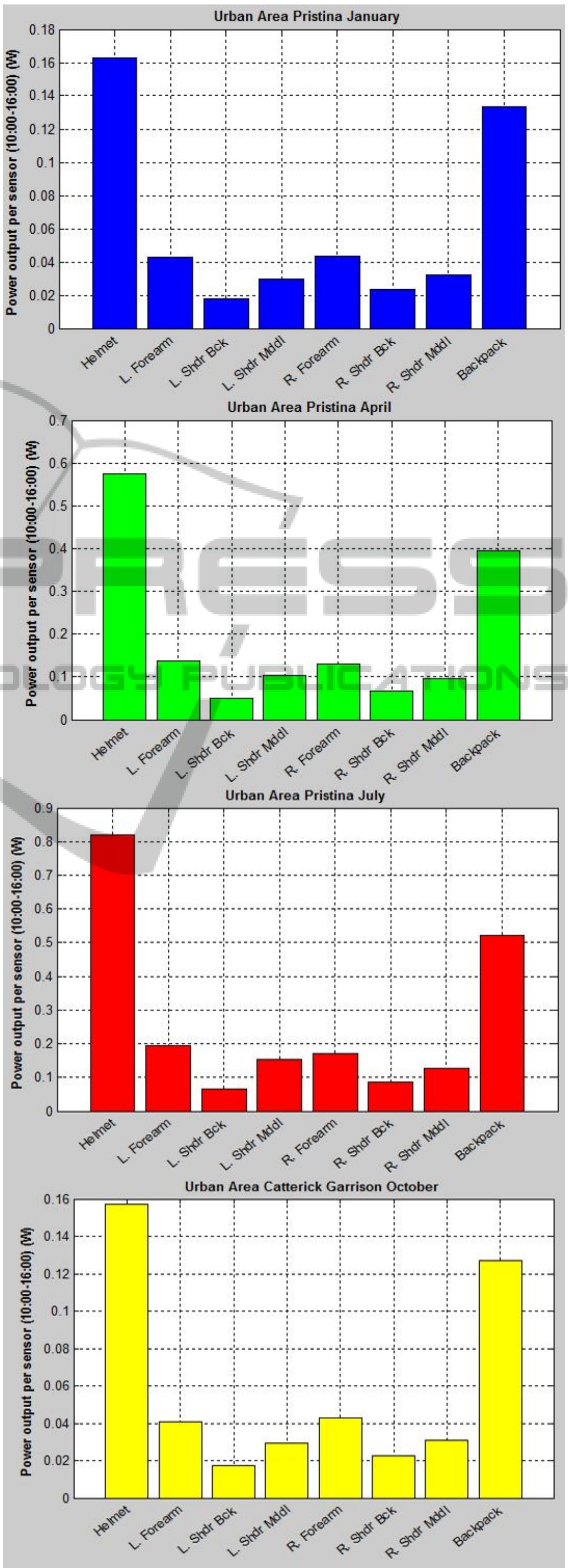

Figure 13: A Urban area scene in Baghdad.