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Evaluation of a measurement and data acquisition system using wireless network technology for microgravity experiments

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Abstract

This paper describes the architecture and algorithm for a data acquisition system for microgravity experiments, and its experimental operational evaluation. The system conducts an experiment by dropping an experimental payload capsule into a 150-m vertical vacuum chamber to produce a microgravity state for a period of approximately 4.6 s. During a free-fall, the system acquires about 446 Mbytes of experimental data, including digital-video and vital data from the falling payload capsule. The system consists of three-layer architecture based on a client/server model, an operator console (client) on the top at ground level and three command managers for exchanging command messages at the middle layer. There are two remote controllers at the bottom layer for measuring instruments and devices in the payload capsule and the release-and-recovery equipment, that exchange command messages using IEEE 802.11 wireless LAN technology. The data format of the command message is optimized to reduce the probability of communication errors in the wireless network link. The experimental data are acquired from the payload capsule and transmitted to the data processing computers via the system. The experimental operational results showed that the architecture for the system can be applied to similar measuring systems.

AMS subject classification:
Keywords: Instrumentation and measurement, data acquisition, wireless network, computer network, computerized instrumentation, microgravity experiments, space technology.

1. Introduction

The technology of wireless local area networks (LANs) is now in widespread use. However, in contrast to wired networks, a wireless network is not generally used for data acquisition systems in large experimental instrumentation systems because a wireless network environment is noisy and unreliable [1, 2, 3]. For scientific experiments where it is necessary to acquire experimental data from moving objects that are physically isolated, wireless LAN technology is a key component in building a low-cost computerized measuring system.

There has been considerable research on the application of wireless LANs. However, none of the applications for an experimental data acquisition system used in a free-falling measuring instrument in a deep vacuum chamber have been described.

When a wireless connection to an access point (AP) is disrupted, data communication for the data acquisition system is suspended in order to scan radio channels and search for an available AP by executing time-consuming 'handover procedures' defined in IEEE 802.11 standards [4]. After discovering an AP, the system must negotiate to establish a wireless connection again. It takes about three to six seconds unless otherwise specified, thus degrading the system's performance.

In this paper, we describe and review an experimental study on a project for a measuremet and data acquisition system using a wireless LAN for microgravity experiments. The results of scientific experiments and research on phenomena occurring in microgravity in space contribute to various scientific fields in which the gravitational force of the Earth is an factor, including material, fluid, combustion and crystallographic sciences [5, 6].

A free-falling capsule in a ground facility, or a small rocket or airplane in a free-fall state, produces a microgravity state for a short period of time, providing physics researchers with a low-cost experimental environment [7, 8, 9, 10]. The Microgravity Laboratory of Japan is an experimental facility [11] in which a microgravity state of less than 10^{-5} G is produced for a period of approximately 4.6 s by dropping a payload capsule into a vertical vacuum chamber in a deep vertical shaft where G is the acceleration due to gravity (≈ 0.981 m/s^2). The final velocity exceeds over 45 m/s.

It is important to obtain the experimental data, using a radio link, from the free-falling payload capsule in a vacuum. However, primary tests showed that ultra-high-frequency band (UHF, 314 MHz band) command-and-data-control links were occasionally disrupted and unstable when the payload capsule entered the vacuum chamber. As a result, the error rate of the command link was too high to acquire data from the payload capsule.

The objective of this project is to satisfy the following specific requirements for microgravity experiments using a low-cost wireless network technology for the measuring and data acquisition system:

1. The payload capsule should maintain the communication links to exchange control data and transfer experimental data to the ground control computer, even when it is stuck in the vacuum chamber.

2. It must acquire experimental data from the measuring instruments in the payload capsule when a free-fall state is detected.

3. It must control the release-and-recovery equipment (RRE) that drops the payload capsule in the vertical vacuum chamber.

4. It must transfer experimental data from the payload capsule immediately after the payload capsule has reached the bottom of the vertical vacuum chamber, which includes digital inputs/outputs (IOs) and digital-video data from the high-speed digital-video cameras.

5. It must be able to monitor the vital physical data of the payload capsule.

6. Furthermore, the payload capsule, RRE and the ground facility comprise heterogeneous implementations, i.e. they are implemented by different hardware components/configurations necessary for a tight vacuum and physical vibrations to cope with experimental environments.

In this paper, we describe a system architecture and techniques implemented for these purposes. Performance evaluation of the system and the results of experimental tests are described in the form of acquired data. The experience gained in operating the system is also discussed.

2. Description

2.1. General Description of the Facility

Figure 1 shows a schematic of the facility with a vertical shaft 150 m deep and 6 m in diameter. The facility consists of a vertical vacuum chamber, payload capsule, vacuum lock chamber, RRE and a large vacuum shutter. For simplicity, apparatus such as vacuum pumps, vacuum valves and vacuum gauges are omitted from the figure.

The vertical vacuum chamber is a cylindrical chamber coaxially built into a vertical shaft and is tapered to a diameter of 1.05 m at the bottom. It is 150 m high and 1.5 m in diameter, comprising a free-fall region ($L = 100$ m) and a deceleration region ($L =$

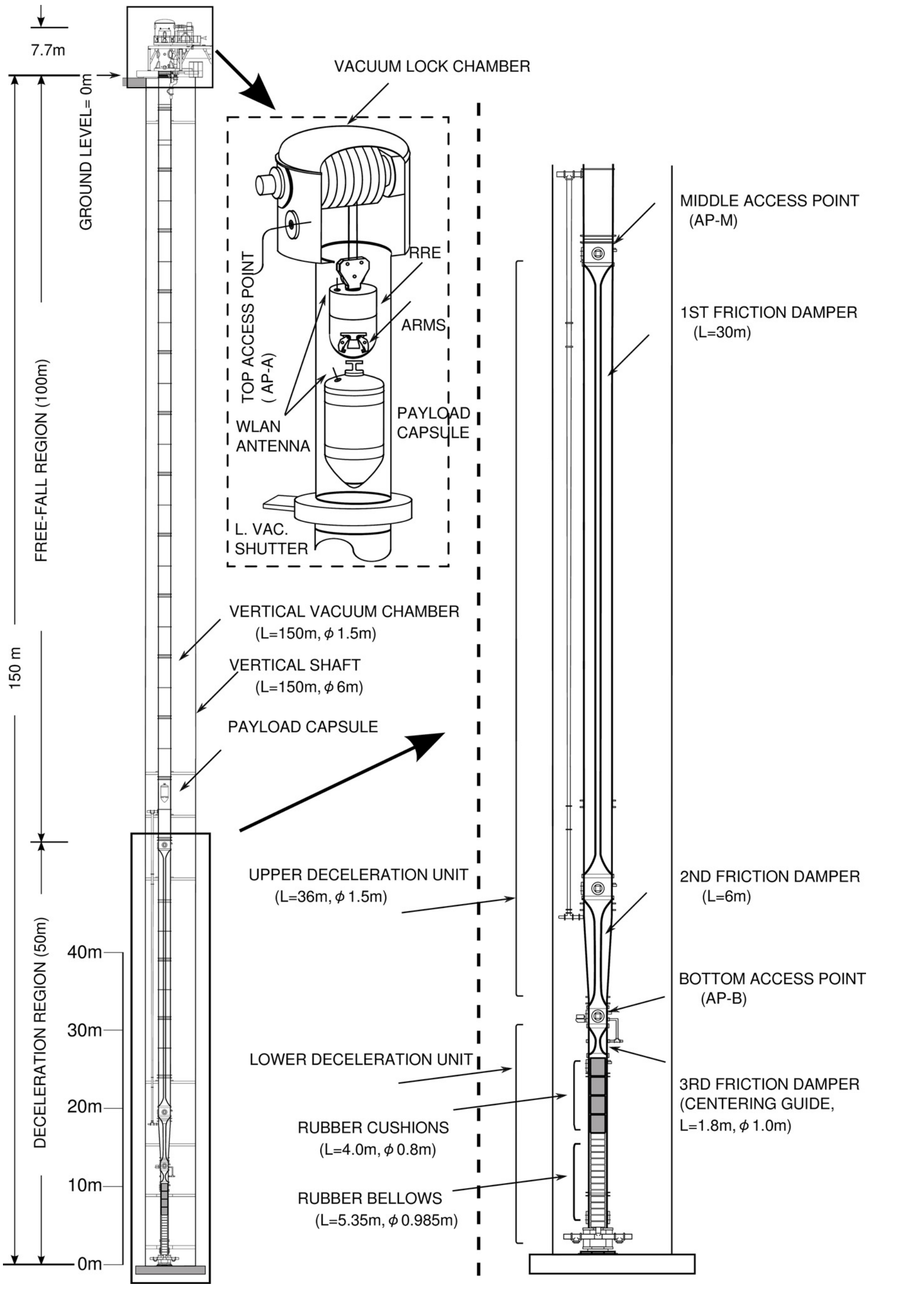

Figure 1: Schematic view of the microgravity experiment facility. The payload capsule is placed by the release-and-recovery equipment (RRE) at the top of the vertical vacuum chamber. Three friction dampers are shown. There are three access points (AP-A, AP-M and AP-B). The top access point (AP-A) is mounted on the viewing port in the vacuum lock chamber 5.5 m above ground level.

50 m). Pressure in the vertical vacuum chamber is evacuated to less than 4.0 Pa to minimize aerodynamic resistance and turbulence for the free-falling capsule.

The RRE ascends/descends using a winch in the vertical vacuum chamber, and has three mechanical arms that catch and fix the hook of the payload capsule when ready for an experiment.

The large vacuum shutter has an aperture diameter of 1.5 m and weighs 2970 kg. It is driven by pneumatic pressure, and separates the vacuum between the vacuum lock chamber and the vertical vacuum chamber below.

The deceleration region has a combined length of 48 m, consisting of three cylindrical friction dampers made of 11-mm-thick carbon-rubber, and flares at each end. It is capable of absorbing the impact of the payload capsule by dragging on the surface of the friction damper. The first friction damper is 30 m long, the second 6 m long, and the third 4.7 m long. The long dampers therefore attenuate the radio signals of the wireless LAN, disrupting communication between computers. At the bottom, there are four cylindrical rubber cushions and the rubber bellows (9.3 m long) are capable of absorbing the remaining decreasing kinetic energy, functioning as air-bags. In this study we focused on the instrumentation of the measurement and data acquisition system for the experiments.

Figure 2 shows the mechanical structure of the payload capsule, which is bullet-shaped and made of aluminum alloy to withstand the deceleration force during experiments. The maximum gross weight of the payload capsule is 1000 kg.

3. Measurement of the Propagation of Wireless LAN signals in the Vertical Vacuum Chamber

To estimate the propagation characteristics of the radio signals for the wireless LAN (IEEE 802.11 a/g, transfer rate = 54 Mbit/s, carrier band = 2.4 GHz), the response times and packet losses were measured. One computer (PC-1) was fixed at ground level (access point AP-A) in Fig. 1, and another (PC-2) was placed at d [m] in the vertical vacuum chamber where d was the depth measured from ground level.

Using the 'ping' standard command utility [12], PC-1 transmitted an "Echo request" packet to PC-2 at d [m]. On receiving it, PC-2 replied with an "Echo response" packet back to PC-1.

The response time (T_R) in seconds is defined as the time from when the Echo request is transmitted from PC-1 to when the Echo Response signal from PC-2 is received.

Figure 3 shows T_R measured at intervals of 5 m from ground level $d = 0$ to 140 m. Dots indicate the maximum response time at each measuring point. The cross points correspond to average response times.

The maximum response time was greater than 300 ms at a depth d below 115 m, where the dampers were installed. Some packet losses were observed in the region below the dampers. The communication in this region was lossy and erratic. However, the average response times were less than 100 ms for all ranges, even below the damper.

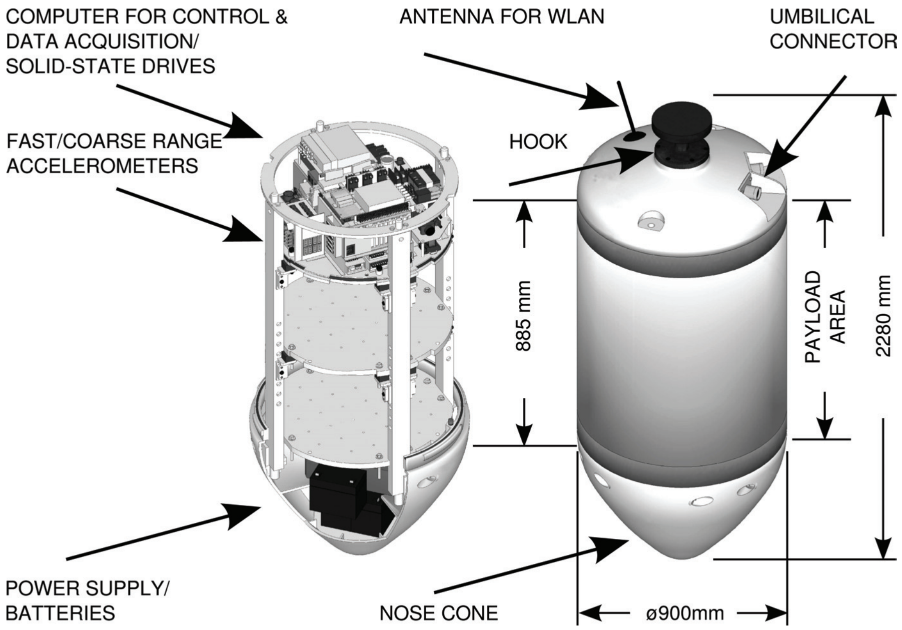

Figure 2: Structure of the payload capsule. The control equipment and communication device, including a computer, accelerometers, solid state disk drives and electronic interfaces for data acquisition, are installed at the top. An antenna for the wireless LAN (WLAN) is shown on the top cover.

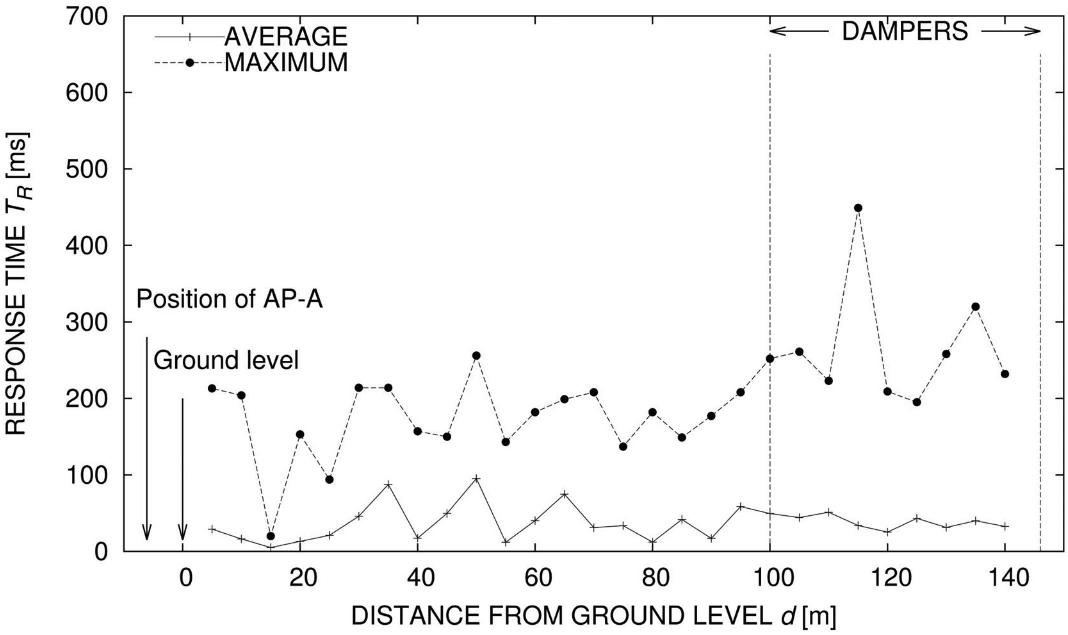

Figure 3: Measured response time T_R [ms] in terms of distance d [m] from the ground level to the payload capsule at d [m].

4. System Configuration

4.1. General

Figure 4 shows a general configuration of the system which is a distributed control system comprising two major layers of a client-server architecture. On the top layer, there is a client at ground level for data acquisition and command control (DACOM) that provides functionality for operator console management. At the second layer, there are two remote controllers that actually control the physical hardware of the instruments as follows:

1. a payload capsule control system (PCCS) that provides data acquisition and control;
2. a controller for the RRE (RRECON); and
3. Data processing computers for users.

There can be more than one data processing computers. However, data processing is beyond the scope of this paper. These are logically linked by a wireless LAN as described in the following sections.

4.2. Network Configuration

To allow the DACOM, PCCS and RRECON to establish communication links, a wireless network (IEEE 802.11) is configured along the vertical vacuum chamber as shown in Fig. 4. The vertical vacuum chamber has viewing ports with flanges (Conflat flange standards: CF-114). There are three access points (AP-A, AP-M and AP-B) linked by the Ethernet IEEE 802.3 network.

At AP-M, a non-directional rod antenna is mounted on the flange of the viewing port 70 m below ground level, i.e., immediately beneath the first friction damper. At AP-B, a rod antenna is mounted on the flange of the viewing port 140 m below ground level, just beneath the second friction damper. The access points are configured to interface between the electrical signals of the wired network and the radio signals of the wireless network. The PCCS and RRECON have the same interface for the wireless networks.This configuration allows the payload capsule to be within radio range even when it is stuck in the deceleration region.

The Transmission Control Protocol/Internet Protocol (TCP/IP) is employed because the measured average response time is less than 100 ms, which is tolerable and recoverable. The TCP/IP is a connection-oriented protocol that provides functions for retransmission when detecting errors or data loss using a check-sum algorithm within the data packet [12]. A sender computer retransmits a data packet until it receives confirmation of delivery from the receiver computer. However, the TCP/IP introduces extra processing time for the computers and increases the network load if the wireless link is unreliable. To reduce the probability of error, the message format for the client/servers is designed as discussed in the next section.

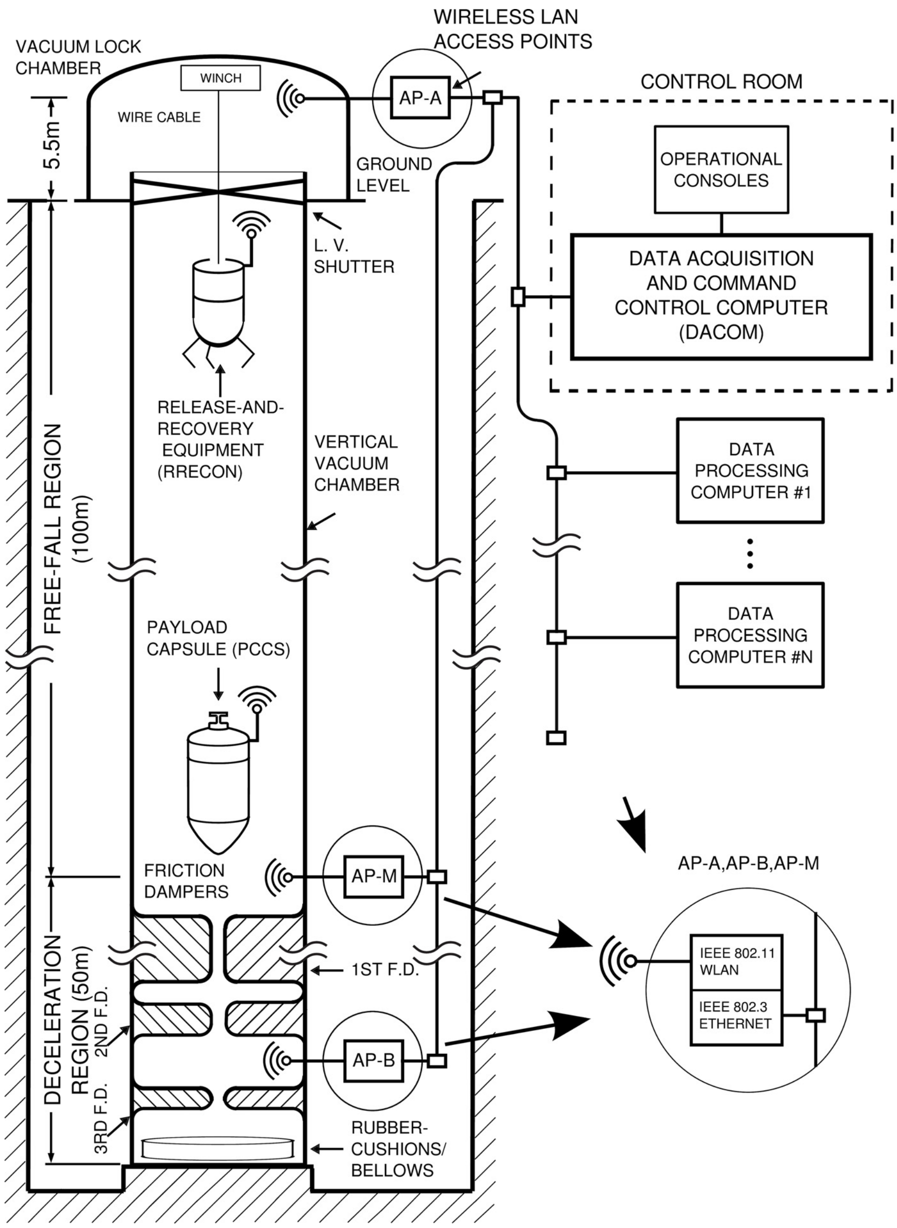

Figure 4: Schematic view of the microgravity experiment facility and the general configuration of the data acquisition and command control computer system for microgravity experiments.

4.3. Data Acquisition and Command Control at Ground Level

Figure 5 shows the schematic diagram of the DACOM and the remote controllers (PCCS and RRECON). The hardware of the DACOM consists of a PC (Intel Core 2 Duo CPU, 3.2 GHz) running under a Windows operating system which is connected to the network. It has two disk drives mirrored to ensure data integrity and error recovery.

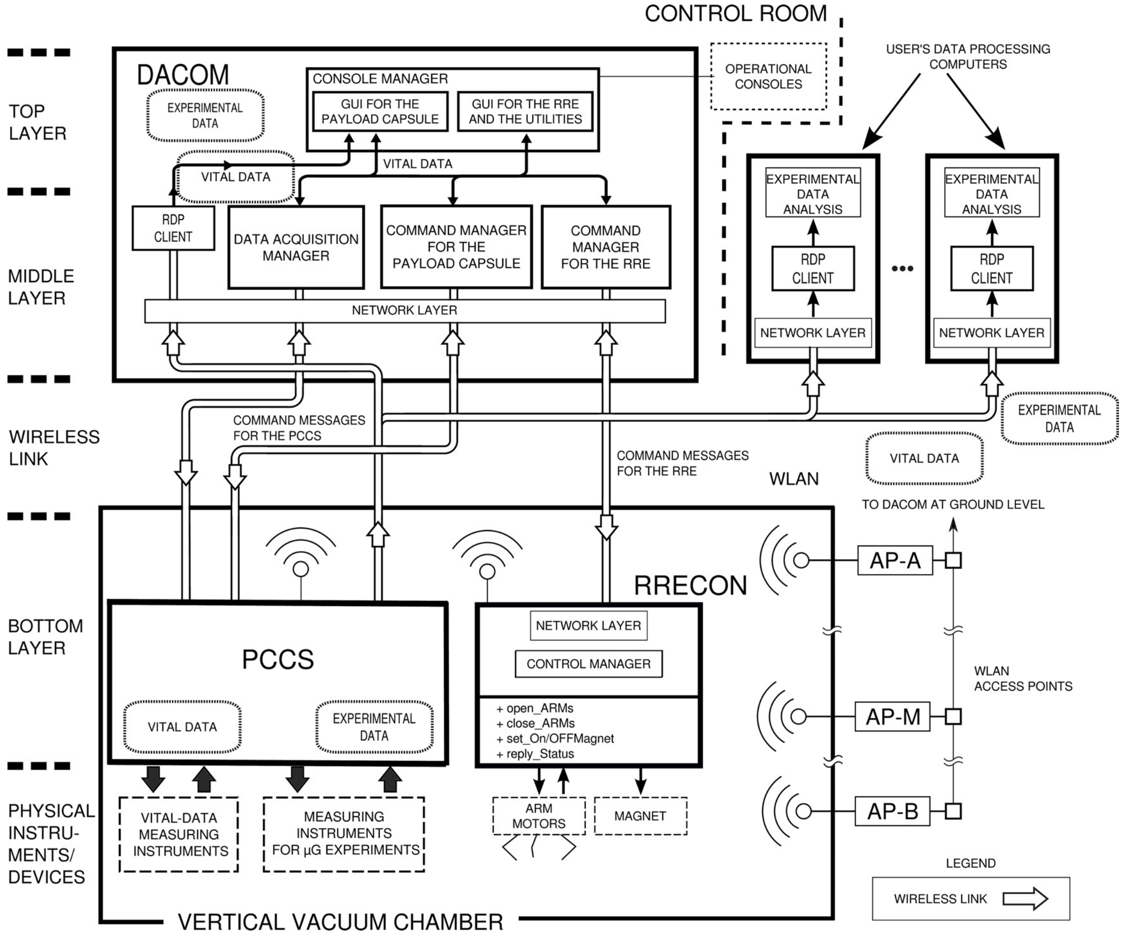

Figure 5: Schematic diagram of the software for the measuring and data acquisition system showing software (solid boxes) and hardware devices/instruments (dashed boxes). Command messages are delivered from the DACOM at ground level to the payload capsule control system (PCCS) and the remote controller for the RRE (RRECON) using the wireless link in the vertical vacuum chamber.

The software of the DACOM comprises three internal layers. On the top layer, there is a console manager for operator console management. In the middle layer, there are three command managers residing between the console manager and the remote controllers. At the bottom, there is a network layer that allows network control for data packet transfer.

The DACOM performs four major functions as follows:

1. It initiates control sequences for the measuring instruments in the payload capsule.
2. It acquires experimental data from the payload capsule, and then transmits the experimental data to a users' computer for data analysis and evaluation.
3. It initiates the controllers for the RRE to conduct experiments.

4. It provides information on the operation of the payload capsule and the RRE, to operational consoles.

4.3.1 Console manager

By communicating with remote controllers, the console manager provides user-friendly man-machine interfaces for console displays, diverse operational aspects of the payload capsule and the RRE. The graphic user interface (GUI) has a menu-driven interface which was developed using Visual Basic with a graphics library. The console manager allows an operator, using the menu, to specify an arbitrary physical instrument to be controlled and/or a component of a remote controller, so that its parameters can then be specified. For example, the operator can find the optimum parameters of an instrument by remotely manipulating and modifying the values of any parameters of the instrument.

The console manager obtains present status information from the payload capsule and RRE by exchanging contiguous messages (called "command messages") and status data.

4.3.2 Design of the command control protocol

There are two command managers: 1) the command manager for the payload capsule; and 2) the command manager for the RRE. They communicate to the remote PCCS and RRECON by exchanging "command messages" and status data. Once the operator at the console has selected an instrument to be initiated, the console manager sends that information to the command manager associated with that instrument. The command manager encodes such information into a command message, and sends it to the remote controller in charge of the specified instrument.

There are two types of command messages: a control message and a status message. The control message is used for initiating a control/measuring sequence for a remote-controller, and must provide 'soft-time critical' operation. The control/measuring sequence may be delayed because of the retransmission procedure if the control message via the wireless LAN is corrupted.

The error rate in terms of the frame length of a command message is considered. Figure 6 shows the structures of the data frames defined in the IEEE 802.11 wireless network and the IEEE 802.3 wired Ethernet network, and the simplified data structure of a TCP/IP datagram [12, 14]. The data field contains a command message with a data length of w bytes.

Under a reliable wired network, it is efficient for a data acquisition system to send one data frame immediately even if the length of the data frame is long, in order to contain information about as many as possible measuring instruments/devices and their parameters for the payload capsule. However, this is not true for a wireless network, particularly when the payload capsule is in a free-fall state in the vertical vacuum chamber.

The probability that n-byte data frame will be correctly received is given by $(1 - p)^{8n}$ where p is the probability of any bit being in error. Thus, for $p = 10^{-6}$ under an optimistically good environment, the probability of error for a full wireless LAN

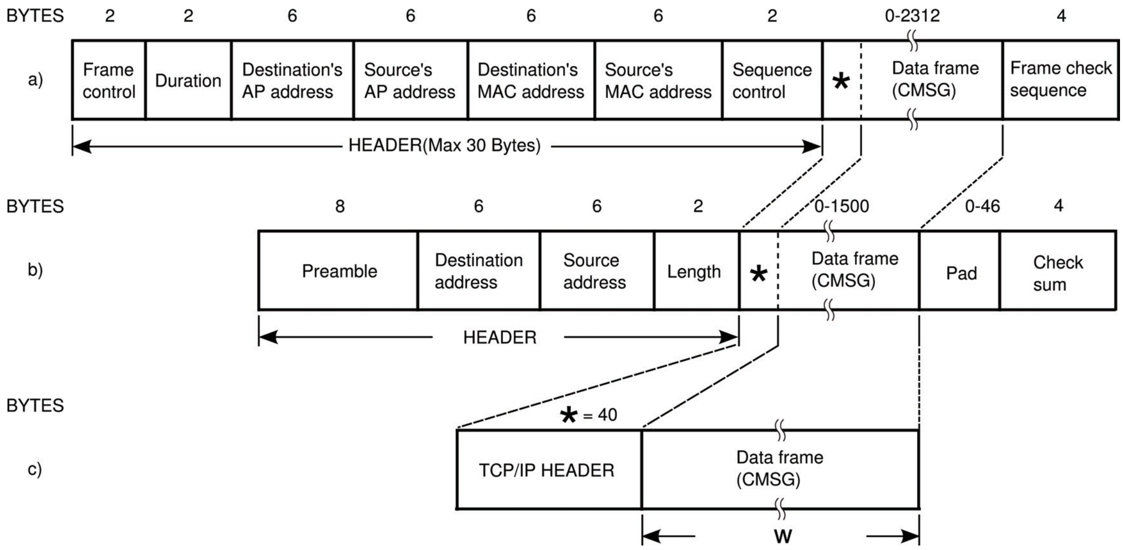

Figure 6: Formats of the data frame for the wireless network and Ethernet network. Each data frame consists of an embedded command message (CMSG) with a data length of *w* bytes; a) Format of the IEEE 802.11 data frame for wireless network (AP=physical address of an access point, MAC=medium-access-control defined in the standards). b) Format of the Ethernet data frame for IEEE 802.3 network. c) Simplified data structure of a TCP/IP datagram.

frame (n = 2346 bytes) is 1.859%, while about 43 bytes in one frame are likely to be corrupted. As a result, the system has to suspend its data acquisition process to carry out time-consuming procedures such as communication-error recovery procedures and/or 'handover' procedures.

Optimization of the communication protocol is essential to reduce the chance of the data frame of a command message being corrupted in an unreliable wireless network environment. This is done by limiting the length of the frame to $w = 2$ bytes, resulting in a total frame length of $n = 76$ bytes. The probability of error for this frame becomes 0.0608%, or, in theory, less than 1 bit in one frame is corrupted. Most command messages are received correctly.

A number of command messages are defined according to the format shown in Fig.7(a). A command message has two data fields. Each data field occupies 8-bits of data. A command message includes the header structure: (i) destination and origin identification codes (IDs) associated with DACOM, payload capsule, or RRECON, and (ii) instruction ID. The command message triggers the remote controller.

Note that this message format is also used for responding short status data back between DACOM, PCCS and RRECON.

Some examples of instructions in the command messages are:

1. Start the preparation sequences for the measuring instruments in the payload capsule ready for a drop experiment.

2. Initiate the measuring sequences for the measuring instruments in the payload capsule.

3. Initiate the release of the payload capsule.

Figure 7(b) shows the header of the status message has the same structure as the command message, but it is followed by variable-length data containing a value (parameter) to be sent to the specific device ID. With regard to the status message, the delay caused by TCP/IP retransmission is tolerable because the status information is, typically, delivered while the payload capsule is not in a free-fall state.

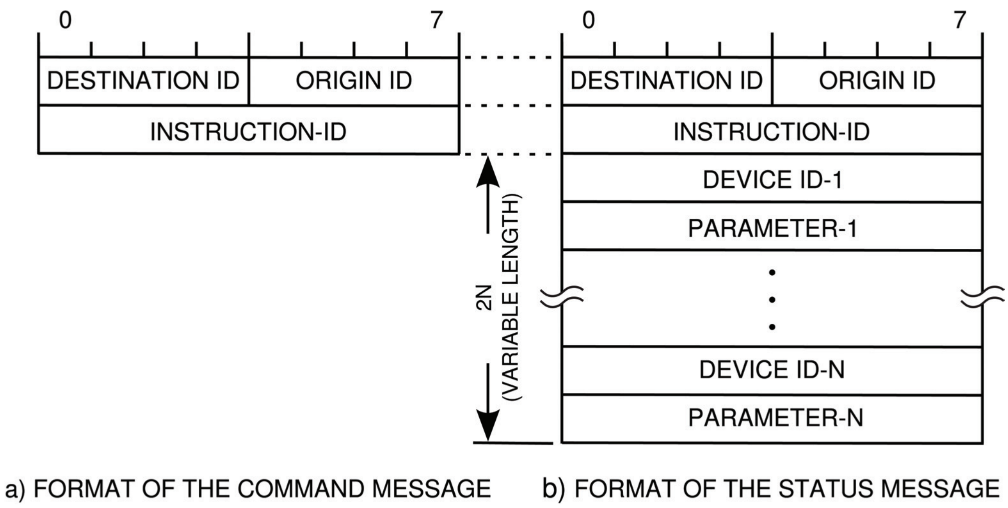

Figure 7: Formats of the command message from a console manager to PCCS and RRE. Each field occupies 8-bits of data. a) Format of the command message. The command message has the header structure: (i) destination and origin IDs (identification code associated with DACOM, PCCS, or RRE), (ii) instruction ID. This message is also used for replying short status data back between them. b) Format of the status message. The status message has the same header structure as the command message. The header is followed by variable-length data containing a value (parameter) to be sent to the specific device ID.

The network configuration described allows only three APs to be accessible in the vertical vacuum chamber. When the loss of a command message is detected during a free-fall experiment, the command manager disconnects the current communication link before the ‘handover procedures’ take place. It then simply chooses one of the IP addresses of the three APs in the order of the most-probably-physically adjacent to the payload capsule; AP-M, AP-B, and AP-A, i.e., in the order of where the signals of radio channels from the APs are expected to be stronger. It can finally establish a communication link to one of the APs. The PCCS and RRECON carry out the same procedure to maintain the communication links between each other.

4.3.3 Data acquisition manager

The Data Acquisition Manager initiates measurements by sending a command message to PCCS. During the experiment, the Data Acquisition Manager acquires and stores the physical data in the payload capsule listed in Tables 1 and 2 as described in the next section.

Table 1: Vital data monitoring instruments for the payload capsule.

Instrument(s)	Range	Resolution
Fast-gravity accelerometers[1]	±1.0 G	<1μG,3.3 ms[2]
Coarse-range gravity accelerometers[1]	±10 G	<1mG,5.0 ms[2]
Vacuum pressure Pirani gauge	0 to 550 Pa	1.3 Pa
Thermometer	−40 to +80°C	±0.3°C
Humidity sensor	0 to 100% RH[3]	±3% RH[3]

[1] three sets for x, y and z directions;
[2] response time;
[3] relative humidity.

Table 2: Standard instruments for digital/analog data acquisition and control devices preinstalled for users in the payload capsule.

Instrument(s)	Description	Resolution/Acquisition time
High-speed digital-video cameras (2 sets)	2000 fps[1]	color, 580 × 434 pixels/frame
Analog-to-digital converters (16 bit)	96 channels	1 μs
Digital output ports	160 ports	200 μs
Digital input ports	160 ports	200 μs
Thermocouples (Type K)	8 channels	330 μs

[1] frame per second

1. It requests the PCCS to capture digital video data, and then create the data files on the local disk.

2. It requests the PCCS to send current gravity and vacuum pressure data.

3. It requests the PCCS to send analog data on vital information using ADCs (96 channels, 16 bits).

4. It triggers any combination of digital output ports (160 ports).

5. It acquires signals at the digital input ports (160 ports).

To transfer the experimental data from the PCCS after a free drop, a Remote Desktop Protocol (RDP) utility is employed. The RDP utility comprises a RDP client and a RDP server. Although there are other protocols prepared for transferring data, such as the File Transfer Protocol (FTP), we focus on RDP in this paper. The RDP is a TCP/IP based protocol that allows a RDP client running on a local computer to share data on a RDP server running on a remote computer [14]. The RDP utilities are freely available under a GNU public license [15, 16] or commercial products for various platforms such as Linux or Windows operating systems. There can be more than one RDP client on the network.

The DACOM has a RDP client, and the PCCS a RDP server. The RDP client at DACOM can share data files and information on the RDP server running on the remote computer (PCCS) via the network. When enabled, the RDP server automatically transfers its experimental data file to the RDP client via the network. The RDP client at DACOM stores the data file on its local hard disk drive. It provides a user-friendly environment for users to analyze data.

There is also a RDP client on the data processing computers for receiving the experimental data.

4.4. Data Acquisition and Control for the Payload Capsule

Figure 8 shows a block diagram of the PCCS. It consists of a control computer, vital monitoring instruments and data acquisition interfaces. The computer and a wireless LAN are installed at the top of the payload capsule, and the experimental measuring equipment is loaded into the payload area in the middle. It employs an Intel Celeron-M CPU, 1.0 GHz clock, 1 GByte memory, two solid-state drives (8+8 GBytes) and compact flash memory (8 GBytes) running under a Windows Embedded operating system. No physical display is necessary at the PCCS.

Table 1 summarizes the principal vital monitoring instruments for the payload capsule including three fast-gravity accelerometers (x, y and z directions), three coarse-range gravity accelerometers (x, y and z directions), a Pirani vacuum pressure gauge, a thermometer and a humidity sensor. The fast-gravity accelerometers have a response time of 3.3 ms and are capable of detecting the microgravity state just after the drop of the payload capsule takes place, although they have a narrow dynamic range of ± 1 G. The coarse-range accelerometers have a dynamic range of ± 10 G with a long response time of 5 ms and a resolution of 1 mG.

The vital data are the internal physical data of the payload capsule, which are required for the facility as well as users, and are stored on solid-state disks. The data are provided to users as part of the research experimental data. The pressure in the payload capsule is monitored by a Pirani vacuum gauge.

Table 2 shows instrumentation for digital/analog data acquisition (input/output/video) devices available to the experimental research users. For the users' experiments, there are two high-speed digital-video cameras (Ci-4, Memrecam) equipped in the payload capsule, which are capable of capturing images at a rate of 2000 frames/s with 580×434 pixels per frame and a 32-bit depth for the color in a pixel. The digital-video data are stored in a frame buffer memory (512 MBytes$\times$2) during the free-fall state. In addition,

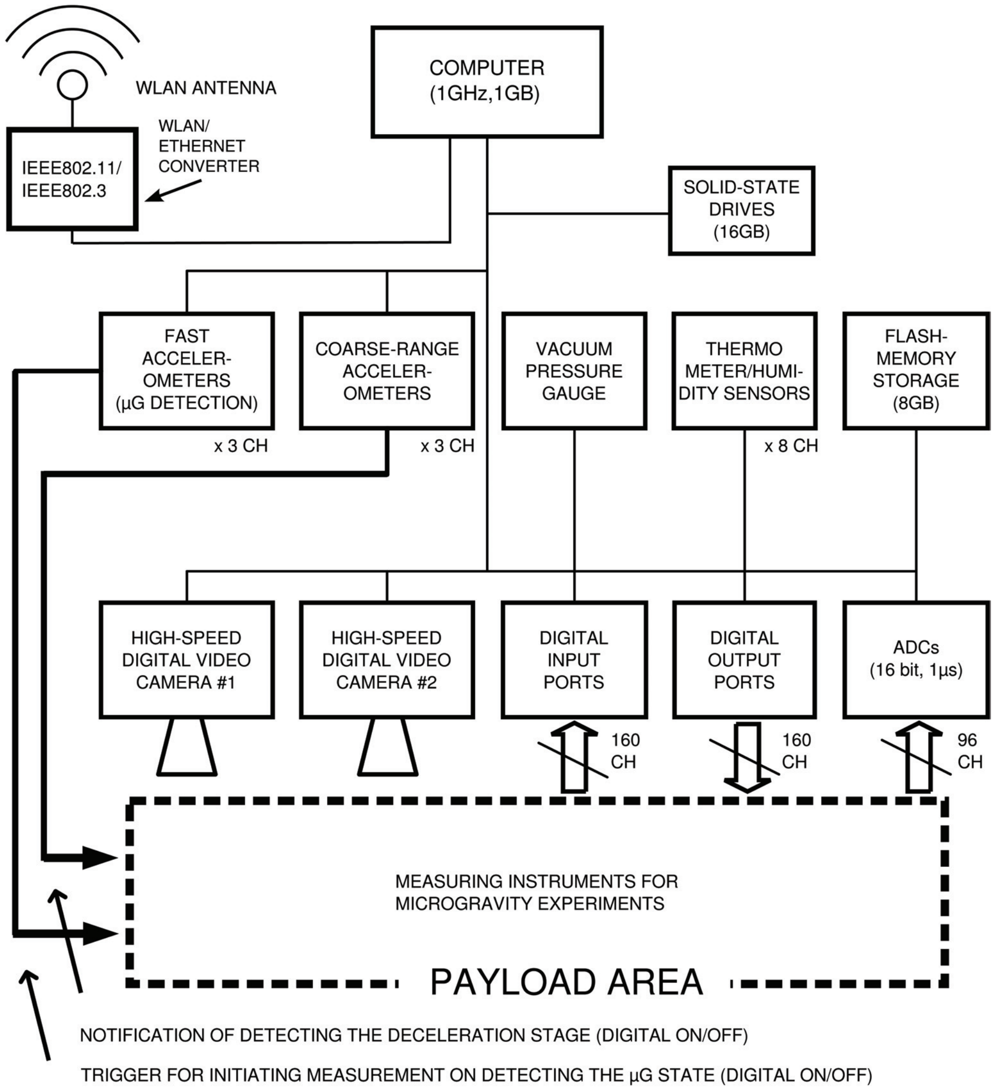

Figure 8: Schematic diagram of the payload capsule control system (PCCS) for the control and data acquisition (DAQ). The dashed box indicates the payload area where users can install their measuring instruments for their research purposes.

digital input/output ports and analog-digital converters (ADC) are provided.

The users can install their own measuring equipment if shorter response times, shorter sampling rates, or higher-precision/resolution, storage capacity or specifications are required for their specific research purposes. These instrumental devices, including the users' measuring instruments, are firmly fixed to the frames of the payload capsule to reduce physical fluctuations caused by gravity during a free-fall experiment.

Figure 9 shows the software structure of the PCCS. The control manager interprets a command message from DACOM. It then executes the command for the specified instrument in accordance with preprogrammed sequences (indicated by a '+' symbol in

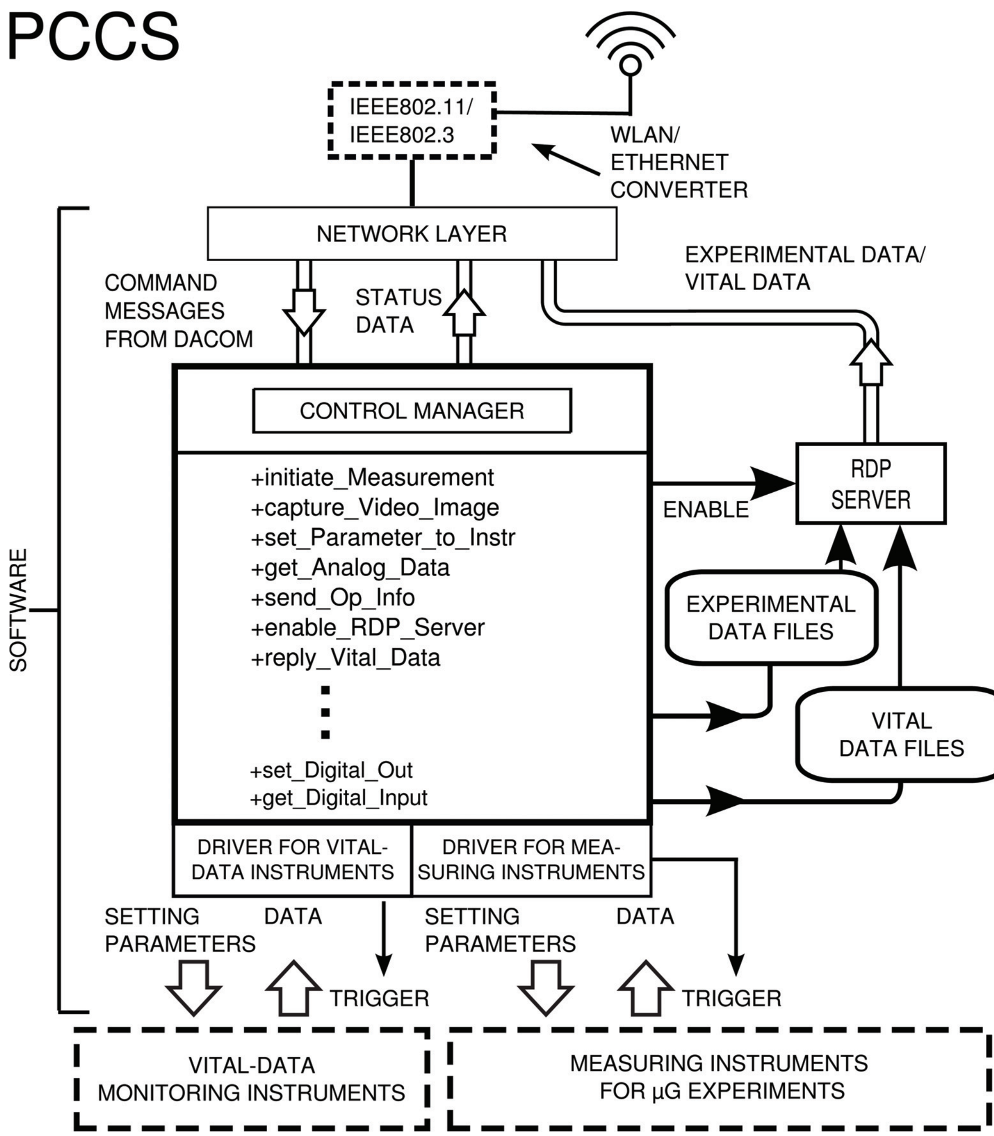

Figure 9: Schematic block diagram of the remote payload capsule control system (PCCS) showing the software (solid boxes) and hardware interfaces (dashed boxes) for the measuring instruments and vital-data monitoring instruments. The PCCS executes the command for the specified instrument in accordance with a preprogrammed sequence indicated by a ‘+’ symbol.

Fig. 9); for example, it sets a parameter to a device/instrument, or requests present status information about the vital data. After completing the command message, the PCCS replies to the command manager with the resultant status information. The command manager forwards such information to the console manager. The PCCS then waits for the next command message. Finally, the console manager depicts present status information, which is sent from PCCS, on the vital data acquisition and monitoring instruments. Details of the algorithm for data acquisition are described in the next section.

4.5. Control for the Release-and-Recovery Equipment

Hardware for the controller of the RRE (RRECON) consists of a programmable logic controller (PLC, Q06HCPU, Mitsubishi), three mechanical arms, an electric magnet, a wireless LAN interface, a mechanical touch sensor and a battery. It is suspended by a wire cable to a winch installed in the vacuum lock chamber. The magnet and the arms hold the hook of the payload capsule with a magnetic force of up to 1700 kg.

The control manager of the RRECON (software) automatically holds/releases the payload capsule using the arms and magnet. After the RRECON establishes a wireless communication link to the DACOM, it is on standby in the vacuum lock chamber, waiting for a command message. The control manager interprets and executes a command message from DACOM for the specified instrument in accordance with preprogrammed sequences (indicated by a '+' symbol in Fig. 5).

5. Data Acquisition by the System

Experimental data are acquired for a maximum period of 9 s, starting from $T = -3$ s before detection of a microgravity state, to $T = +6$ s. During a free-fall of the payload capsule, each of the digital input/output ports and ADCs are automatically triggered by the PCCS. An operator can monitor this status information on the operational console.

5.1. Description of the Automatic Measuring Sequence

Prior to a drop, the payload capsule is lifted to a maximum internal height of 150 m, by the RRE using the winch. The RRECON holds it by controlling its mechanical arms, and by energizing the electric magnet and using its magnetic force. When ready, the DACOM transmits the initial release command to the RRECON, and the drop command to the PCCS notifying the start of initial sequences for the experiment.

On receiving an initial release command, the RRECON opens the arms holding the payload capsule. However, the magnet holds the payload capsule until it stabilizes itself in a stationary state, thus helping reduce the initial horizontal G-jitter.

On receiving the drop command, the PCCS executes the initial sequence that triggers data acquisition for the instrumentation of the digital/analog data shown in Tables 1 and 2 in a preprogrammed manner set by the users. The RRECON de-energizes the magnet to drop the payload capsule into the vertical vacuum chamber when it receives the final-release command message from the PCCS.

On detecting a pre-microgravity state of less than the negative acceleration μGz$=$ -0.1 G using the fast accelerometers after the payload capsule is released, the PCCS notifies the user's experimental equipment (Fig. 8). It allows the experimental equipment an initial time margin to activate data acquisition. This is done in real-time by generating an electronic trigger signal using electronic hardware. It reduces the complexity of the

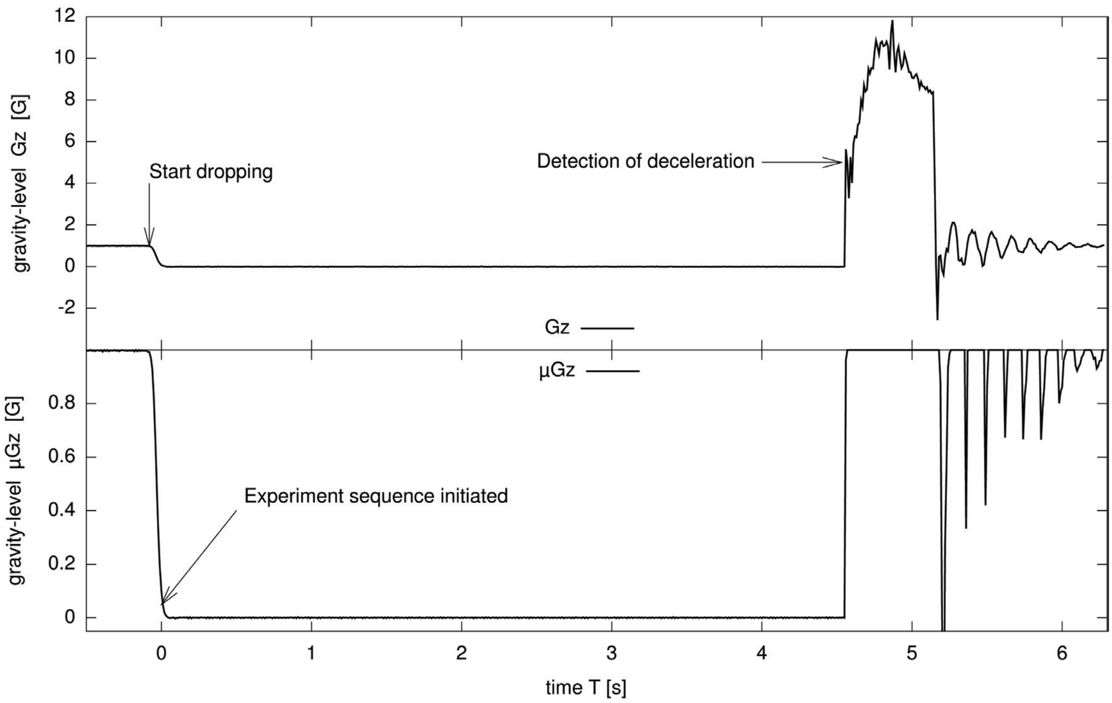

Figure 10: Typical vertical gravity level traces G_z measured by the system. (upper) Vertical gravity level G_z measured using the coarse-range accelerometer. (lower) Vertical gravity level μG_z measured by the fast-gravity accelerometer.

software requirements for time-critical tasks as well as the overhead on the computer load.

During the free-fall state, the digital/analog data as well as the operational and control information on vital data, are acquired and collected by the PCCS which creates data files containing the digital/analog data on solid-state drives. Digital-video data are also captured by the two high-speed digital-video cameras, and are stored in data files in the flash-memory storage.

In the last stage of the free-fall, approximately 4.6 s, the payload capsule reaches the first damper. On detecting vertical deceleration exceeding $Gz \geq +5.0\,\text{G}$ using the coarse-range accelerometer, the PCCS notifies the experimental instruments and DACOM. It helps finalize the measurement, i.e., flashing the remaining experimental data, buffered in the static memory, into the solid-state drives and/or the flash-memory storage, to ensure that there is no accidental loss of data.

5.2. Uploading Sequence for the Experimental Data

After a free-fall drop, the PCCS enables its RDP server to allow for the data acquisition manager of the DACOM to access the experimental data files, including digital-video data through the wireless LAN link. Vital data files are also accessible by the data acquisition manager through the wireless LAN. An operator can monitor the progress

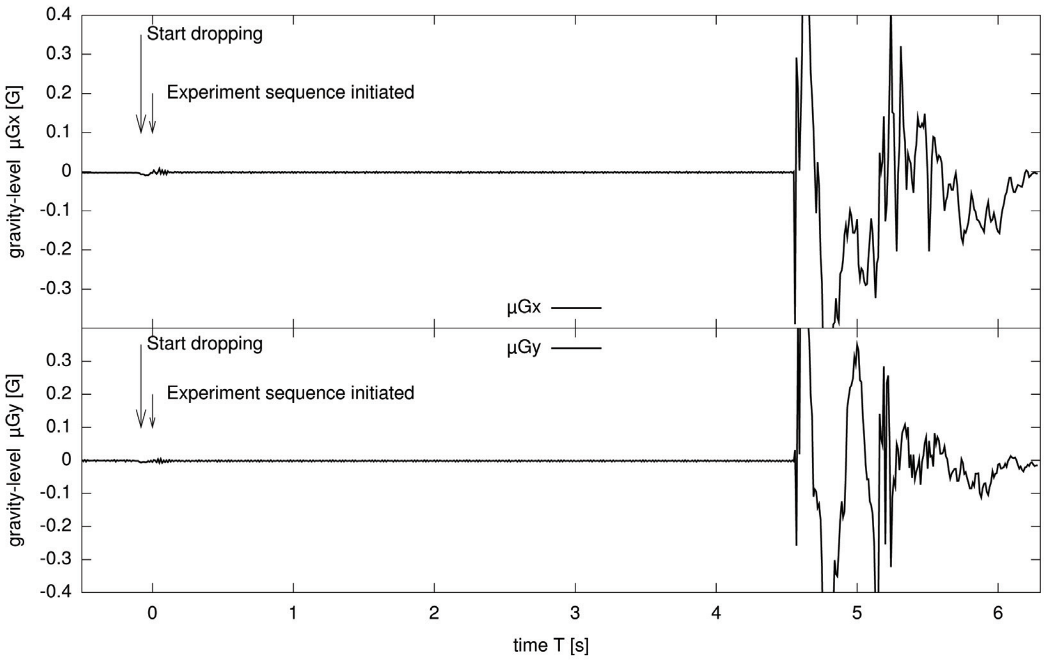

Figure 11: Typical horizontal gravity level traces measured by the system. (upper) x-component of the horizontal gravity μG_x. (lower) y-component of the horizontal gravity μG_y.

status at the console while the experimental data are uploaded to the DACOM. Finally, the user's data-processing computer can receive the experimental data using its RDP client through the wireless LAN link.

6. Experimental Test Results

To evaluate the system, a number of experimental operational tests were carried out for free-fall experiments. Figure 10 shows typical gravity level curves measured at intervals of 10 ms in the payload capsule. The vertical gravity level G_z measured using the coarse-range accelerometer is shown in the upper figure. The drop sequence for the payload capsule took place at $T = -1.5$ s (not shown in the graph) after opening the arms. The payload capsule was released at $T = -30$ ms by de-energizing the magnet. For ease of observation, the time $T = 0$ indicates the time a negative acceleration below $\mu G_z = -0.1$ G was detected. On detecting this negative acceleration value using the fast accelerometer μG_z, the PCCS generated the trigger signal for notifying the experimental instruments. The fast accelerometer was saturated at over $\mu G_z \geq +1.0$ G from approximately $T = +4.53$ s after deceleration began.

The coarse-range accelerometer for the vertical direction G_z exceeded +5.0 G at $T = +4.61$ s, indicating that a microgravity state was attained for 4.61 s after the release of the payload capsule. The payload capsule stopped completely approximately 6.40 s after release. The last impact of the vertical deceleration gravity on the payload capsule reached 11.7 G at the completion of an experiment.

Figure 11 shows the horizontal gravity level curves measured by the fast-gravity accelerometers for μG_x and μG_y in the payload capsule. The upper figure shows the horizontal gravity of the x-component μG_x and the lower figure shows that of the y-component μG_y.

During a free-fall experiment, experimental data, including physical internal data, typically of 446 Mbytes, were acquired. While the payload capsule stayed in the friction damper, experimental data were successfully transmitted to the DACOM without difficulty. It usually took about 180 s to transfer the experimental data. Even when the payload capsule was placed below the bottom dumper, a communication link between the payload capsule and DACOM was established with no difficulty. The users were able to acquire the experimental data as well as vital data of the payload capsule, and could examine and analyze the resultant experimental data immediately after a free-fall.

Results of tests were reproducible, proving the reliability of the measuring and data acquisition system. No message loss for the wireless network communication between the DACOM, payload capsule and RRECON was observed.

7. Discussion

The main objective of this project was to satisfy the requirements for the data acquisition system using wireless network technology to obtain experimental data, even under a noisy and unreliable wireless network environment, from a free-falling capsule in a lossy 150 m vacuum chamber. The payload capsule and the release-and-recovery equipment have heterogeneous implementations. Initial results for the measurements shows that there were packet losses in the vacuum chamber.

The architecture and a data acquisition algorithm are described to overcome this. The communication protocol and the data format for the command messages were optimized to reduce the probability of error. Using the communication protocol in combination with the architecture, the system was capable of carrying out measurements and data acquisition.

This was validated by a number of experimental tests. Experimental data for the microgravity experiments including digital video data as well as physical data of the payload capsule were successfully acquired by the system. The experimental data were automatically transferred to the DACOM at ground level and finally to the data processing computers for users to analyze.

The architecture can run on different computers placed in the physically distributed measuring system. One of the major attractions of the methodology discussed in this paper is that it can be applicable to other areas, at low cost, for measuring and monitoring systems for physically-isolated moving remote objects which have heterogeneous configurations.

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