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Smart Pantries for Homes

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Abstract

A smart pantry holds non-perishable household supplies and automates the purchasing and delivery of their replenishments. By relieving its user from the chore of keeping the home stocked of essentials, it provides convenience and peace of mind not only to elderly individuals but also busy people of all ages. This paper describes two alternative smart pantry designs and tradeoffs. Underlying methods and technologies used for their implementation are also described.

1 Introduction

In recent years, population of developed and developing countries is aging at a rapid rate [1, 2]. There is a growing need for low-cost, easy-to-use, and dependable devices and services designed to help the elderly live independently, improve their quality of life and reduce the cost of their care. Examples of these devices include object locators for finding misplaced household and personal objects and automatic and robotic helpers for enhancing physical dexterity and accessibility [3, 4]. Given the fact that the average percentage of population 65 or older will soon exceed the percentage of population under 15 in these countries, one expects that such devices may someday be as demanded as iPoD, game consoles and robotic toys.

Another example of consumer electronics for the elderly is smart pantries for storage of nonperishable supplies. Such a pantry monitors its contents and automates the just-in-time replenishment of objects in it. Thus, it relieves of its user from the chore of keeping objects such as shampoo and detergent on hand. Smart pantries are for convenience of elderly individuals, as well as busy people of all ages who have no time or interest to shop (or order) for boring but essential household supplies.

This paper describes two alternative smart pantry designs and implementations: the *picture-id version* and the *bar-code version*. The difference between the versions arises from differences in the technologies used for content capture and object identification. The picture-id version, called *PID pantry*, uses an overhead camera to capture its contents. In purchase orders sent by a PID pantry to the suppliers, each object to be delivered is specified by a picture captured by the camera prior to the removal of the object from the pantry. The supplier must process the photo image, either manually or automatically, in order to identify the brand and size of the object. For this reason, the usability of PID pantry is not ideal from the supplier's point of view. It is easy to use from owner's point of view, however. Other than making sure that nothing blocks the view of the camera, the user can treat a PID pantry just like a dumb pantry. The bar-code version, called

BAC pantry, identifies objects in it by their bar codes. Because every object in every purchase order is unambiguously identified by a bar code, BAC pantries are easy to use from the supplier's point of view. On the other hand, the user must scan the bar code of every kind of objects in the pantry. Unless given a bar code before the supply of the kind runs out, the pantry will not be able to order replenishment automatically.

A natural question is why not RF identifiers (RFID). If every household object were to come with a smart tag, a pantry equipped with a RFID reader can easily maintain inventory as the user moves objects in and out of the pantry. This version would have the advantages of both PID and BAC versions and none of their disadvantages. In fact, this is how smart cabinets used in hospitals for storage of medical supplies work. Unfortunately, the RFID-version of smart pantries for home use is still not economically feasible and is likely to remain so for some time to come [5]. A cost of tens of cents per tag is low enough for tagging expensive medical supplies but is orders of magnitude too high for tagging ordinary household items individually.

Smart pantry is one of a family of appliances that are the research focus of the SISARL project [6, 7]. SISARL devices and appliances are consumer electronics of convenience, personal safety and health maintenance. Targeted users are elderly individuals who may have some functional limitations, but are still in relative good health, live independently and, most likely, in homes of their younger years. Like assistive devices and home care equipments, SISARL devices must be easy to use and highly dependable. However, assistive devices (e.g., [8 – 15]) typically assume a smart operating environment equipped with computer(s), Internet and, often, a variety of smart sensors; their targeted users, being in need of help in daily living, subscribe to assistive services, and so on. These assumptions are unrealistic for SISARL devices. To keep the costs of SISARL devices to a fraction of the costs of typical assistive devices is another challenge.

Following this introduction, Section 2 discusses assumptions and constraints common to both versions of smart pantry. Section 3 describes of their architectures and implementations. Section 4 describes the techniques used by PID pantry for object identification purpose and summaries preliminary experimental results. Section 5 describes wireless sensing schemes for BAC pantry. Section 6 summaries the paper and discusses future work.

2 Commonalities and Differences

As stated earlier, a smart pantry is used to hold non-perishable household supplies. It knows its contents and can automate their replenishments. For example, each pantry in Fig. 1 knows that a bag of paper towels is on the top shelf. When the last roll is removed, the pantry contacts a supplier of user's choice and requests the store to deliver a replacement bag.

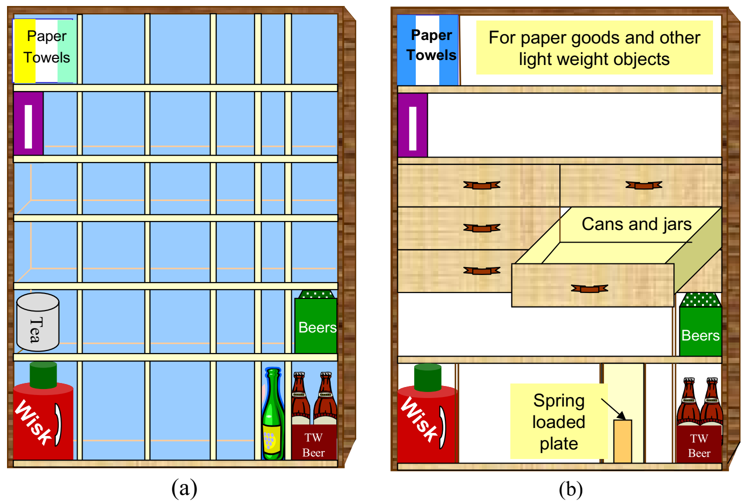


Fig. 1 Smart Pantries

An underlying assumption is that one or more grocery and discount stores have agreed to receive and process purchase orders sent by the pantry on the user's behalf and deliver each order by a specified date. Alternatively, the panty may be provided to the user by a supplier. The information required for contacting suppliers, placing orders and arranging payments and deliveries were entered into the pantry at initialization time, together with information on user preferences. By default, purchase orders are sent via messages over a dial-up connection, but a user with broadband internet access can configure the pantry to place orders via Internet.

Both versions use a keypad, a microphone, a speaker and a recorder to support user-pantry interaction. These I/O devices may be parts of a phone (or a computer), rather than being dedicated to the pantry. The microphone, speaker, and recorder form an audio interface that records voice of the user and plays back user voice interleaved with pre-recorded pantry voice. By allowing the pantry to interact with the user, the audio interface makes the pantry friendlier and more tolerant to misuse.

Like ordinary dumb pantries, the storage space in a smart pantry is divided into compartments. Fig. 1 shows two configurations. The picture-id version is constrained to use the one in Fig. 1(a). The fact that each compartment is clearly defined by a rectangular boundary simplifies the extraction of pictures of individual compartments from a picture of the entire pantry. In contrast, shelves in the pantry in Fig. 1(b) are not necessarily divided vertically. Rather, each compartment on a shelf corresponds to a switch that is in the front of the shelf and a spring-loaded plate that moves perpendicular to the shelf. (This construction is similar to the ones used in drug store shelves.) When a plate is at the front of the shelf, as illustrated by the plate on the bottom shelf in the figure, it presses the switch closed, indicating that the corresponding compartment is empty. The compartment is nonempty when the plate is pushed towards the back of the shelf by an object, leaving the switch open. By sensing the states of the switches, a BAC pantry can distinguish empty compartments from non-empty ones. The bar-code version is constrained to use this configuration.

Both versions require that objects in each compartment are identical. They are designed to accommodate concurrent insertions and retrievals of objects by multiple users.

As we will see in the next section, a PID pantry cannot tell whether objects in two or more compartments are identical. By default, it will order replenishment when the last of the objects in any compartment is removed, even when some other compartments may contain more of the same objects. Moreover, it is constrained to order all objects from the same default supplier with the same *replenishment time* (i.e. the length of time-to-delivery interval). The bar-code version does not have these limitations.

3 Architecture and Implementation

In our discussions, we refer to compartments by 2-tuples of rows and columns. As an example, (3, 4) refers to the fourth compartment from the left on the third shelf from the top. We use *rows* and *columns* to mean numbers of rows and columns of compartments in the pantry.

3.1 PID Pantry Design

Fig. 2 and Fig. 3(a) show the physical components of a PID pantry. The pantry consists of a base unit and a remote unit. The base unit contains a digital camera, together with the processing and storage modules that do most of the work. The base unit is mounted overhead so that the camera can capture a front view of the pantry shelf. The remote unit contains all the I/O devices and is within an easy reach of the user. It also provides access to the supplier(s). The units are connected wirelessly.

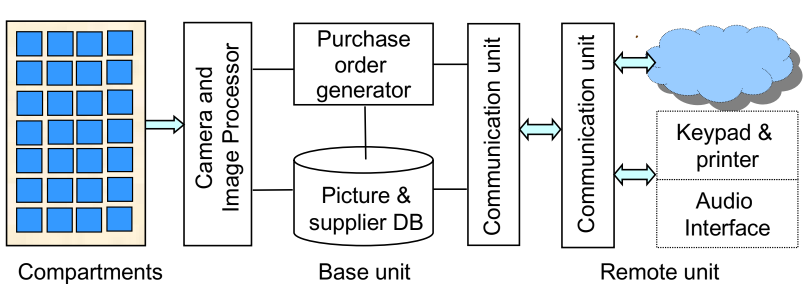
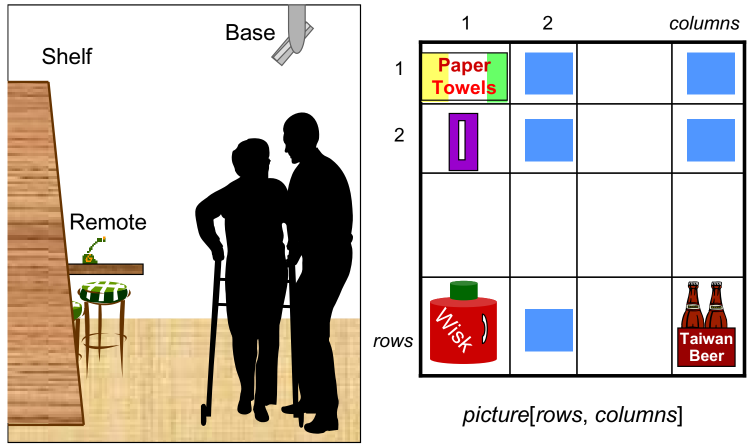


Fig. 2 Components of a PID pantry



(a) (b)

Fig.3 Arrangement and Contents

```
Initialization:
    Initialize supplier information and user preferences;
    Command the camera to take current_picture of the pantry;
    previous_picture = current_picture;
    Process current_picture to identify compartment boundaries,
    Determine numbers of rows (rows) and columns (columns);
    Allocate array picture[rows, columns];
    Initialize elements of picture to EMPTY;
while pantry runs, periodically do {
     Command the camera to take current_picture of the pantry;
     if (current_picture != previous_picture) {
         for every compartment (i, k), do {
             Get current_content of (i, k) from current_picture;
             if (current_content  !=  picture[i, k] ) {
                  if (current_content  == EMPTY) {
                       Insert picture[i, k] to items_to_order list;
                       picture[i, k] = EMPTY;
                  } else {
                       picture[i, k] = current_content;
                  }
              }
          }
          Generate a purchase order for objects in items_to_order;
       }
}
```

Fig. 4 Operations of PID pantry

Fig. 4 describes the operations of the pantry. The pantry is empty during initialization. By capturing and processing the *current_picture* of the pantry, the pantry controller determines the boundaries of the compartments and values of *rows* and *columns* and captures *EMPTY,* a picture of an empty compartment. (For the sake of simplicity, our discussion assumes that all compartments look the same when empty. This restriction can be easily removed.) It then allocates an array, called *picture*[*rows, columns*], to store pictures of individual compartments and initializes every element to *EMPTY.*

During normal operation, the controller examines the contents of the pantry periodically (e.g., every 200 milliseconds) by having the camera take a snapshot of the pantry at the start of the period. When the controller finds the new snapshot (*current_picture*) is essentially identical to the previous one (*previous_picture*), it does nothing. Otherwise, it extracts the picture *current_content* of every compartment (*i, k*) from *current_picture* and compares it with the one stored at *picture*[*i, k*]. Thus it determines whether the compartment has changed from being empty to non-empty and vice versa. In the former case, it stores the new picture of the compartment at *picture*[*i, k*] for use later. In the latter case, the compartment has just been emptied. The pantry inserts the picture stored at *picture*[*i*, *k*] into the list of objects to be ordered and then sets the element to *EMPTY*. The list thus generated can be printed and used as a shopping list, if the user chooses to shop rather than relying on the pantry, or sent by the pantry to a supplier as a purchase order. Fig. 3(b) shows what *picture* may contain at some time. The solid colored boxes indicate *EMPTY*. To ease the task of automatic object identification, the pantry also sends *EMPTY* in every purchase order.

We note that a basic PID pantry such as one described here merely extracts pictures of the objects in compartments. It cannot identify the objects. As we will see in Section 4, the object identification function for determining the brands and sizes of objects from their pictures requires significantly more processing power than what is needed to segment a big picture into smaller pictures. The function also requires a database of high quality pictures of objects to be identified. By off-loading this function to servers at the supplier side, the pantry is kept as simple as possible. (The base and remote units can be built from commodity digital camera and cordless phone, respectively.) On the other hand, because the pantry cannot distinguish objects from each other, it has the limitations mentioned Section 2.

3.2 BAC Pantry Design

Again, objects in a BAC pantry are identified by their bar codes. With user's help, the pantry acquires incrementally the bar codes and voice descriptions of all objects ever stored in it.

Some of the date structures maintained by the pantry are shown in Fig. 5. Each element of the *compartment array* on the left contains the state of a compartment and a pointer to the description of the object in it. The right half of the figure depicts the information on each object, which includes the bar code and a recorded voice description of the object. The user may choose to keep some kind of objects in multiple compartments and requests the pantry to order replenishment only when all the compartments holding them become empty. In that case, the *compartments* field gives pointers to structures of compartments holding the same kind of object. The user of a BAC pantry has the flexibility of ordering different kinds of objects from different suppliers and specifying different replenishment times. This is why the pantry maintains supplier and user preference information on each kind of object individually.

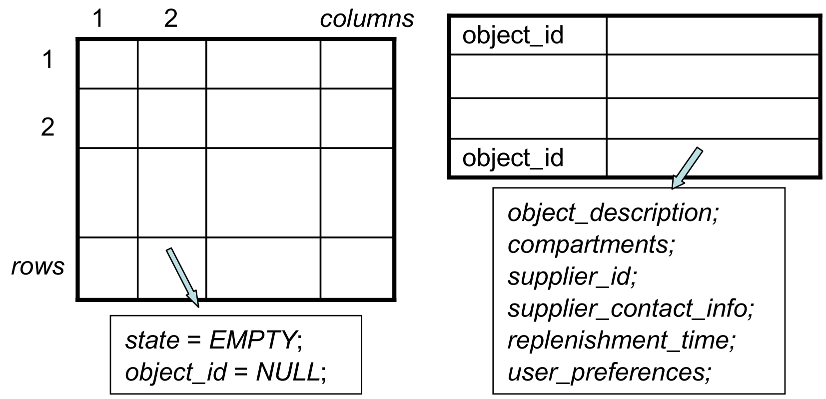


Fig. 5 Compartment and object descriptions

The architecture of BAC version is similar to that of PIC version. A difference is, obviously, that the remote unit of a BAC pantry includes a bar code scanner. Another difference is that BAC version uses an array of switches to monitor the states (i.e., empty/non-empty) of the compartments. Whenever the state of a compartment (*i, k*) changes from empty to non-empty, the pantry controller acquires, with the user's help, the bar code and a voice description of the object just placed in the compartment. When the state of (*i, k*) changes from non-empty to empty, the controller puts the bar code of the object that was in the compartment in the *items_to_order* list, sends a purchase order to the supplier of the user's choice and then marks the compartment empty. Details on the operations and implementation of an interrupt-driven BAC pantry controller can be found in [4]. That implementation assumes that switches used to monitor compartment states are wired to the pantry controller interface. We will return in Section 5 to describe wireless sensors that can be used to turn an existing dumb pantry into a smart BAC pantry.

Like the PIC version, multiple users of a BAC version can place objects and remove them in any order. Scenarios described in Figs. 6 and 7 involve two users and call them Alice and Bob. In the figures, descriptions of user and pantry actions are in italic. Text in regular font gives dialogs between the user and the pantry via the audio interface. The object names are uttered in recorded user voice. They are interleaved with pre-recorded pantry voice in the dialogs.

Fig. 6 illustrates user-pantry interactions during placement of objects into the pantry. In the first scenario, the user and pantry work together to put objects into the pantry: When putting an object in an empty compartment, the user scans the bar code of the object to be placed in the compartment, gives a voice description of the object if the object is new to the pantry, and then puts the object in the compartment. When the user puts an object into a non-empty compartment, nothing needs to be done.

The second scenario describes what may happen when the user hurryingly puts an object in an empty compartment without providing the pantry with a bar code. In this case, the compartment is marked non-empty but the object id remains unknown.

Putting away objects in load-pantry mode:

Bob: *Press "**Load Pantry**" on keypad to start putting two objects in pantry.*
Pantry: *Turns on bar code scanner.*
Bob: *Scans bar code of a pack of Taiwan Beer.*
Pantry: *Failing to find the bar code in database, says*: You just scanned an object. Please tell me what it is.
Bob: Taiwan beer.
Pantry: *Records "Taiwan beer"*. You said Taiwan beer.
Bob: *Puts the pack of beer in compartment (6, 4).*
Pantry: You have just put Taiwan beer in (6, 4).
Bob: *Scans a bag of paper towel.*
Pantry: *Finding the bar code and voice descriptions of the object, says:* You have a bag of paper towel.
Bob: *Puts the paper towel in compartment (1, 2) and walks away.*
Pantry: You just put a bag of paper towel in (1, 2).
Pantry: Shuts down the scanner and goes to standby when timeout expires.

Putting away object without bar code:

Alice: *Puts a bag of paper towel in empty compartment (1, 3) and walks away.*
Pantry: *Sensing an object is put in (1, 3), turns on the bar code scanner.* You just put an object in (1, 3). Please scan its bar code.
Bob: *Ignoring the pantry, puts a pack of Taiwan beer in (6, 4).*
Pantry: *Marks (1, 3) nonempty; leaves object_id for the compartment NULL.* You just put an object in (6, 4). Please scan its bar code.
Bob: *Scans the pack of Taiwan beer.*
Pantry: (6, 4) now has Taiwan beer. Please scan the object in (1, 3).
Bob: *Ignoring the pantry, walks way.*
Pantry: *Shuts down the scanner and goes to standby when timeout expires.*

Fig. 6 Putting objects in BAC pantry

Removal of object with bar code:

Alice: *Remove the last bottle of beer from (6, 4).*
Pantry: You took the last of Taiwan beer from (6, 4). Please press "***Yes***" if you like it reordered, "***No***" if you do not want it reordered.
Alice: *Press "**Yes**" key.*
Pantry: I will order Taiwan beer from Costco and ask them to deliver it in (*default*) 3 days. If you want it sooner or later, please enter the number of days followed by the # sign.
Alice: *Enters "1#" on the keypad and walks away.*
Pantry: I will ask Costco to deliver Taiwan beer tomorrow. *Generates and sends order. Goes to standby when timeout expires.*

Removal of without bar code :

Alice: *In the midst of putting away supplies, scans a bag of paper towel for the first time.*
Pantry: You just scanned an object. Please tell me what it is.
Bob: *Removes the last of object with unknown bar code from (4, 3).*
Pantry: *Noticing the bar code of the removed object is unknown, attends to the removal and says:* You just removed the last of the object in (4, 3). I do not know what it is. Please scan it now.
Bob: *Lets Alice scan the removed object (Taiwan beer) and walks away.*
Pantry: You took the last of Taiwan beer from (4, 3). I will reorder it from Costco and ask them deliver it tomorrow. If this is not what you want, please press "***No***" now; otherwise, press "***Resume*** " to load pantry.
Alice: *Hurrying now, puts the paper towel in (4, 3) and walks away.*
Pantry: *When wait_for_resume timeout expires, assumes that the object in (4, 3) is unrelated to the one Alice scanned earlier.* You just put an object in (4, 3). Please scan its bar code.
Pantry: *When timeout expires, marks (4, 3) nonempty, object_id unknown. Generates and sends order for beer. Goes to standby.*

Fig. 7 Removal of objects

The first scenario in Fig. 7 illustrates removals of objects when their bar codes are known. As stated earlier, a supplier and a replenishment time have been selected for all objects at initialization time. By default, the pantry will send to that supplier a purchase order and request the object be delivered within the replenishment time. The user can ignore the voice confirmation from the pantry when the defaults are acceptable. Otherwise, the user can cancel the order or, with the help of the pantry, change the preferred supplier and replenishment time during the normal removal process. (Detailed scenarios illustrating this user-pantry interaction and error recovery can be found in [4].) When objects are placed in and removal from the pantry concurrently, the pantry would pay attention to placements of objects when their bar codes are known, since it can reorder the objects from the suppliers listed in its file. In contrast, when the bar code of a removed object is unknown, as the second scenario in Fig. 7 illustrates, the pantry attends to the removal immediately, prompting the user to scan the removed object.

Errors during placements and removals are inevitable. When the user does not follow the normal sequence of scan and placement, some objects in the pantry may have no bar codes and some objects may have wrong bar codes. These errors are recoverable. An error of the former type is known to the pantry. It handles the error by asking the user to scan the object at the time of the removal. When an object has a wrong bar, the voice confirmation from the pantry during the removal process provides the user with an opportunity to discover the error and initiate a corrective action. An error is unrecoverable when it causes the pantry to fail in ordering correct replenishment in time. Unfortunately, unrecoverable errors can occur when the user ignores the voice of the pantry when it tells the user the information it has on the content of the compartment.

4 Object Identification Module

To make PID pantries easy to use, a supplier needs to add to its order processing server an object identification module (OIM) that processes pictures contained in purchase orders from smart pantries and returns as results the brands, sizes and locations of the objects. Roughly speaking, the module identifies the object in each picture by determining which image among all images of known objects in its database best matches the image it extracts from the input picture.

The OIM works faster and more accurately when the number of candidate images to match is small. Hence, the module maintains for each user a small repository of images of objects that have identifiers and are known to have been purchased by the user. Most of time, the module only needs determine which of these objects most likely matches the objects in the input pictures. It only needs to search the much larger database of images of all objects in the supplier's inventory on rare occasions when the user orders something new.

4.1 Approach and Algorithms

The flow chart in Fig. 8 gives an overview of OIM operations. The major steps are background subtraction, low-level image processing, color matching and shape context-based search.

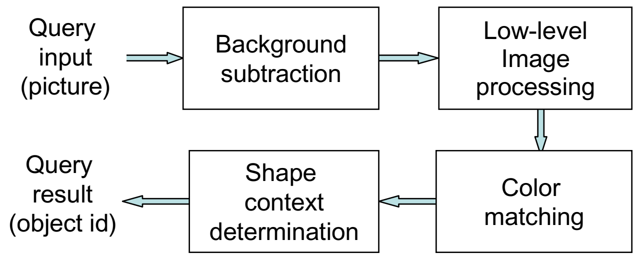


Fig. 8 Object identification operations

***Background Subtraction* (*BS*)** The first step is to extract the foreground image of the object from the input picture of a non-empty compartment. For this work, the module uses as background image the picture, *EMPTY,* of empty compartments, which the pantry sends in the purchase order. Let $B(x, y)$ and $I(x, y)$ be the values of the background image and the input image at pixel (x, y), respectively. A way to determine the value $f(x, y)$ of the foreground image at (x, y) is to let it be $I(x, y)$ if the absolute difference between $I(x, y)$ and $B(x, y)$ is larger than a preset threshold T; otherwise, $f(x, y)$ is equal to 0. The module uses this simple way to determine the values of most foreground pixels. It chooses the threshold T based on the statistics on pictures sent by the pantry in the past.

***Low-Level Image Processing* (*LLIP*)** BS step does not work well for all pixels because of shadow points and noises. The foreground image produced after the BS step may have fragments that originally belong to the same component. A goal of the LLIP step is to fix this problem. In this step, OIM carries out morphological operations (i.e., dilation followed by erosion) several times [16]. It then executes a connected-component-labeling process to label distinct objects in the foreground. It considers objects that are smaller than a threshold size as noises and removes them from the foreground image.

Shadow is another problem that must be dealt with. Some shadows may be of large enough sizes to be retained after the connected-component-labeling process. The OIM applies a shadow removal algorithm described in [17] to remove them. The algorithm compares the hue, saturation and intensity values between the foreground and the background images and uses the equation below to distinguish shadow pixels from the foreground pixels.

$$SP_k(x,y) = \begin{cases} 1 \quad if \quad \alpha \le \dfrac{I_k^V(x,y)}{B_k^V(x,y)} \le \beta \\ \quad \wedge (I_k^s(x,y) - B_k^S(x,y)) \le \tau_S \\ \quad \wedge \left| I_k^H(x,y) - B_k^H(x,y) \right| \le \tau_H \\ 0 \quad otherwise \end{cases}$$

$I_k^V(x,y)$, $I_k^S(x,y)$, and $I_k^H(x,y)$ in the equation above represent, respectively, the intensity, saturation value, and hue values of a foreground pixel at (x, y). B_k^V, B_k^S, B_k^H, on the other hand, represent these values of a background pixel at (x, y), respectively. α, β, τ_S, and τ_H are thresholds chosen on the basis of lighting condition and pre-determined statistics. $SP_k(x, y) = 1$ represents that the pixel under consideration is a shadow pixel and is to be removed from the foreground image.

***Color Matching* (*CM*)** The foreground object obtained after the LLIP step is a candidate for object recognition. The OIM uses a coarse-to-fine matching mechanism. For coarse search, it works with color and layout of the object. Specifically, it uses two standard descriptors in MPEG-7 [18], dominant color and color layout, to perform coarse level object recognition. It calculates the dominant colors from R, G and B channels, quantizes 256 colors into 32 bins, and then distributes all pixels belonging to an object into these bins. The top 3 bins of each channel are picked to represent the channel for comparison. The comparison metric is the Euclidean distance, and the weights assigned to channels are identical.

Since the dominant color is a global feature, it does not carry any relational information. Therefore, the OIM also includes color layout and uses a quad-tree to express it. This way, a different object that has the same set of dominant colors or an identical object that is placed in different orientations will not be mistakenly chosen in the coarse search stage.

***Shape Context-Based Search* (*SCBS*)** In addition to the dominant color and color layout, a detailed description of the foreground object to be recognized is required for the fine search process. For this purpose, the current version of OIM uses a shape context-based descriptor [19, 20] to characterize the shape of an object.

To compute the descriptor, the OIM first applies the Canny edge detector [21] to extract a silhouette of the target object. (The Canny type detector is one of the best existing edge detectors but cannot guarantee the full extraction of complete silhouette.) It then selects r control points from the detected silhouette. The distance between every consecutive control point pair is almost equal except the broken parts due to incompleteness of the silhouette. Fig. 9 shows an example. The picture in the top row shows an object. The picture in the left of the bottom row shows the almost complete silhouette produced by Canny edge detector. The picture in the right shows the r selected control points generated from the silhouette.

Next, the OIM computes log-polar histograms corresponding to the r control points for each object to be compared. Each log-polar histogram characterizes the relationship among the r chosen control points of the object [19, 20]. To derive the histograms, the OIM uses a circle mask to cover every control point of the target object. It first divides the circle into 12 30-degree bins along the circular direction and then divides each bin in the radius direction into 5 bins equally according to the log of the radius. The circle mask after partition is shown in Fig. 10(a). The log-polar histogram of a control point can be found by putting the center of a circle mask on the control point and calculating its log-polar histogram. Fig. 10(b) illustrates this calculation.

Fig. 9 Example on context-based descriptor

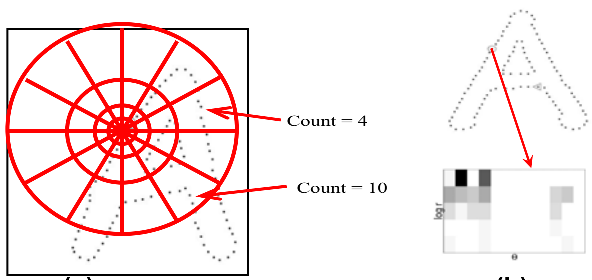


Fig. 10 A circle mask and a log-polar histogram

After computing sets of r log-polar histograms of the objects in pictures contained in a purchase order, the OIM puts them and pre-computed sets of r histograms of known objects contained in the user's repository into a bipartite graph. As the final step, the module calculates the degrees of matches according to Hungarian algorithm [22].

4.2 Preliminary Performance Results

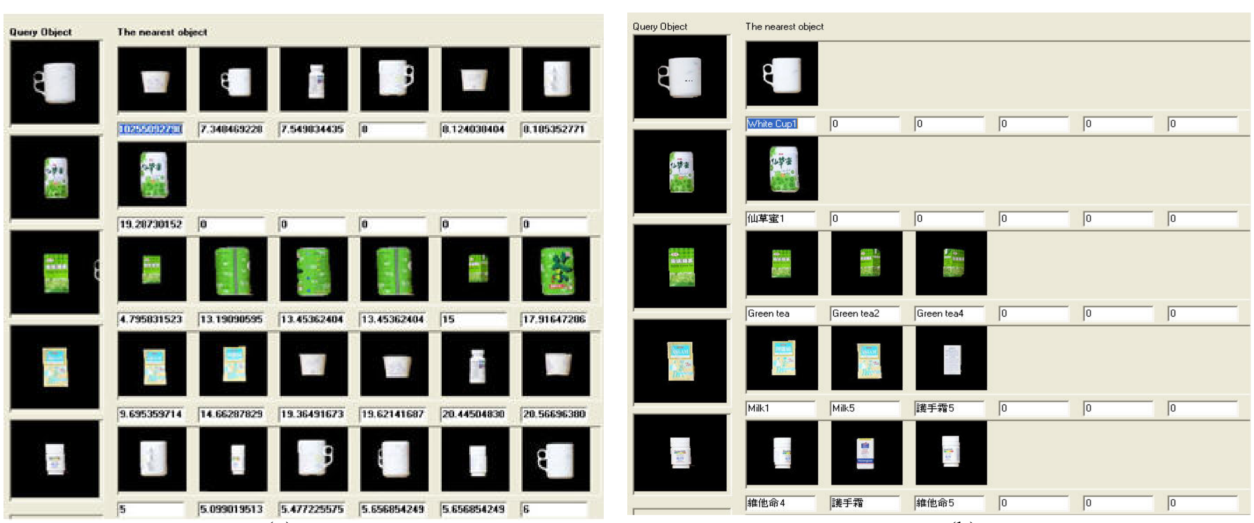
In order to test the efficiency and effectiveness of the OIM, we constructed a database of the forty objects and a small pantry. The objects are shown in Fig. 11. In an experiment, we processed a purchase order containing pictures of five objects in ways described above. Fig. 12 shows how the pantry looks when empty and how the five objects looked in the pantry before they were removed

The images extracted by the OIM are in the leftmost column in Fig. 13(a). The remaining six columns in the figure give the top six (or fewer) candidate objects retrieved by the module for each input object after the coarse search (i.e., the CM step). Obviously, a coarse search does not eliminate enough candidates. However, the coarse search process is very fast, allowing the module to quickly screen the database and obtain a significantly smaller set of candidates. In the fine search process, the module applied the shape context feature on candidate objects and derived much more accurate results as illustrated in Fig. 13(b). The speed of the fine search process is slower than the coarse search due to the computation of shape context, but the more time consuming process is applied on only to a small number of candidate objects.

Fig. 11 objects in database

(a) (b)

Fig. 12 Empty and loaded pantry



(a) (b)

Fig. 13 Results of coarse and fine searches

5 Wireless Sensor Array

In the BAC version described in Section 3 and [4], switches for monitoring compartment states are connected by wires to the sensor interface on the pantry controller I/O bus. This construction is suitable for pantries specially built to be smart. However, wiring up an existing dumb pantry to make it smart would be an unattractive option. A better alternative is to use wireless sensors, allowing the user to configure a dumb pantry (or a part of the pantry) into a smart BAC pantry as easily as a PID pantry.

A wireless binary sensing scheme for this purpose is described in [4]. That scheme uses passive RFID tags, one per compartment. The controller contains a reader. The shelves and spring-loaded boards are constructed so that the tag corresponding to a compartment is shielded from the reader when the compartment is empty but is visible to the reader when the compartment is non-empty. The controller determines the states of the compartments by reading the tags periodically. While the scheme works in principle, it is not ideal. Metal objects in the pantry can shield the reader from some visible tags. Solutions (e.g., use of multiple antennae) to this problem lead to added cost and installation difficulty.

SISARL project is developing an ultra-low-cost wireless sensor array (WSA) for use in BAC pantries, as well as other SISARL devices (e.g. medication dispensers [7].) A WSA contains a coordinator and a number of sensor nodes. When used in a BAC pantry, the coordinator is a part of the controller, which is AC powered. For each compartment, there is a sensor node (SN), which is battery assisted. Let N be the number of sensor nodes in the WSA, and the id's of the nodes are 1, 2, …, N.

The WSA resembles a wireless personal-area network (see http://www.ieee802.org/15/) in physical size, but because of its applications, a WSA has many different characteristics:

- N is small (say less than 265)
- The distances between nodes and the coordinator are small (say less than 5 meters).
- Each SN contains a sensor that has a small number of states. (Sensors in BAC pantries have only two states.)
- A SN sends a fixed size frame containing its id and one byte of data on the new state whenever the state of its sensor changes.
- The chance that more than a few (e.g., 3) nodes having frames to send within one second is negligibly small.
- The chance that a SN has two or more frames to send within a second is negligibly small.
- The response time of sending a frame should be in order of tens of milliseconds.

The combination of low data rate and small physical size means that the end-to-end delay between nodes and the coordinator in a WSA is negligibly small compared to the time required to send a bit. This fact makes the simple WSA medium access control (MAC) scheme illustrated by Fig. 14 possible.

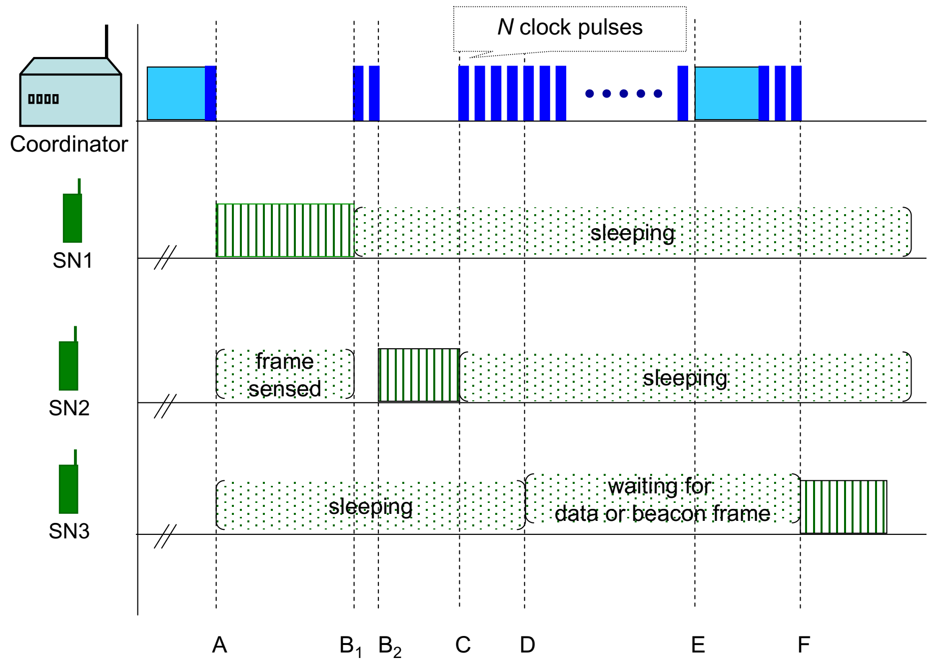


Fig. 14 MAC of WSA

According to the scheme, when no sensor node has frames to send, the coordinator continuously polls the nodes by sending a beacon frame followed by a sequence of clock pulses. – In Fig. 14, beacon frames depicted by light-colored square boxes on the top time line, and the clock pulses are depicted by narrow dark boxes. After sending each clock pulse, the coordinator pauses to listen briefly. Hearing no data frame, it continues to send clock pulses. After it has sent the N-th pulse in the sequence, it repeats a beacon frame followed by clock pulses.

If the coordinator hears a data frame immediately after it sends a clock pulse, it switches to receive the data frame. At the end of the data frame, it sends clock pulses, listens in between pulses, switches to receive if hears a data frame; otherwise, it sends a beacon frame after it completes the sequence of N clock pulses.

Medium access by the sensor nodes are prioritized according to their ids: the smaller the id, the higher the priority. Specifically, when a node with id k has a data frame to send, it waits until it hears a beacon frame or data frame and then counts the clock pulses after the end of the frame. If it hears a data frame before the kth clock pulse, it waits until the data frame ends and then counts clock pulses again. The node commences to send its data frame, whenever it hears the kth clock pulse in a pulse sequence after a beacon or data frame.

Fig. 14 illustrates the operations of sensor nodes with ids 1, 2, and 3. At the start, both SN1 and SN2 have frames ready to send. They wait until they hear the beacon frame from the coordinator. At time A, SN1 sends its data frame after it hears the first pulse following the beacon frame. Its transmission causes SN2 to wait. Since SN1 no longer has data frame to send, SN2 gets to send at time B_2 after hearing two clock pulses following the data frame from SN1. At time C, no node has data to send, and the coordinator begins to send a sequence of *N* clock pulses. Suppose that SN3 awakes at time *D* in the midst of the sequence. It must wait until it hears the next beacon and then starts to count. In this example, SN3 gets to send at time F after the third clock pulse.

To estimate the worst-case response time in a WSA, suppose that the time to send a data or clock pulse is 10 microseconds. The coordinator takes 20 microseconds to send a clock pulse. The array has 250 sensor nodes. Beacon and data frames are 100 bits and 50 bits long, respectively. The times the coordinator takes to send a beacon frame and 250 pulses are 2 millisecond and 5 milliseconds, respectively. Suppose that three lowest-priority nodes, SN248, SN249 and SN250, have data frames to send immediately after the coordinator starts to send clock pulses. The SN250 must wait for the time required to send 4 sequences of clock pulses, one beacon frame, and two data frames. So, the worst-case response time of SN250 is approximately 25 milliseconds.

6 Summary

This paper describes the PID and BAC versions of smart pantry. One can get a PID pantry by adding a digital camera and pantry electronics to any dumb pantry that has compartments. The pantry owner can use it much like a dumb pantry when placing and removing objects. On the supplier's side, pictures in each purchase order sent by the pantry must be processed to identify the objects in the order and find their inventory control codes for locating the objects to be delivered. The process can be automated by the suppliers. The paper describes an object identification module designed for this purpose.

From both the technical and usability points of view, the BAC version represents a reasonable compromise. The supplier can rely on the bar codes in purchase orders to identify and locate the objects to be delivered. However, the users must scan the content of each compartment at least once before the last object in it is removed. For users who are willing to follow this rule, a bar-code version is sufficiently user friendly and reliable.

Much work remains to be done to access the merits of the OIM and WSA described here. We are refining the algorithms used in OIM so that it can accurately identify objects in low resolution pictures and determining the minimum required resolution for object identification with acceptable accuracy. The WSA is being prototyped. An assumption is that the transmission is sufficient error-free as to make error detection and recovery unnecessary. Some form of ARQ will be added if this assumption is found invalid in our evaluation.

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References

[1] Japan Assistive Products Association, http://www.jaspa.gr.jp/, April 2003.

[2] "Global Aging," *BusinessWeek*, January 31, 2005.

[3] Jane W. S. Liu, *et al*, "Reference Architecture of Intelligent Appliances for the Elderly," *Proceedings of International Conference on System Engineering*, Las Vegas, NV, August 2005.

[4] Jane W. S. Liu, *et al.*, "User Scenarios and Designs of Smart Pantry, Object Locator and Walker's Buddy: Consumer Electronics for the Elderly," Technical Report No. TR-IIS-O5-OO7, Institute of Information Science, Academia Sinica, Taiwan, July 2005.

[5] R. Glidden, *et al*. "Design of Ultra-low-cost UHF RFID Tags for Supply Chain Applications," *IEEE Communications*, August 2004.

[6] http://sisarl.org. SISARL: Sensor Information Systems (and Services) for Active Retirees and Assisted Living.

[7] P. C. Hsiu, *et. al*, "A General Model for Medication Scheduling," Technical Report No. TR-IIS-05-008, Institute of Information Science, Academia Sinica, Taiwan, October 2005.

[8] S. Helal W. Mann, H. El-Zabadani, J. King, Y. Kaddoura, and E. Jansen, "The Gator Tech Smart House: A Programmable Pervasive Space," *IEEE Computer*, March 2005.

[9] E. Dishman, "Inventing Wellness Systems for Aging in Place," IEEE *Computer,* May 2004.

[10] A. Pentland, "Healthwear: Medical Technology Become Wearable," IEEE *Computer*, May 2004.

[11] D. A. Ross, "Cyber Crumbs for Successful Aging with Vision Loss," *IEEE Pervasive Computing*, April 2004.

[12] http://architecture.mit.edu/house, Changing Places Consortium, MIT.

[13] http://www.cc.gatech.edu/fce/seminar/fa98-info/smart_homes.html, FCE Smart House Research Survey, Georgia Tech.

[14] http://www.futurehealth.rochester.edu/, Center for Future Health, University of Rochester.

[15] http://marc.med.virginia.edu/projects_smarthomemonitor.html, Marc smart home, University of Virginia.

[16] J. C. Russ, *The Image Processing Handbook, Fourth Edition*, CRC Press, July 2002.

[17] A. Prati, I. Mikic, C. Crana, M. M. Trivedi, "Shadow Detection Algorithms for Traffic Flow Analysis: A Comparative Study." *IEEE Conference on Intelligent Transportation System,* Oakland, California, pp.340-345, 2001.

[18] Y. Deng, B. S. Manjunath, C. Kenney, M. S. Moore, H. Shin, "An Efficient Color Representation for Image Retrieval." *IEEE Transactions on Image Processing,* Vol.10, No.1, pp. 140-147, January 2001.

[19] S. Belongie, J. Malik, J. Puzicha, "Shape Matching and Object Recognition Using Shape Contexts." *IEEE Transactions on Pattern Analysis and Machine Intelligence,* Vol.24, No.4, April 2002.

[20] G. Mori, S. Belongie, J. Malik, "Efficient Shape Matching Using Shape Contexts." *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 27, No.11, pp. 1832-1837 November, 2005.

[21] J. Canny, "A Computational Approach Edge Detection." *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol.8, No.6, pp.679-698, November 1986.

[22] R. C. Gonzales and R. W. Woods. *Digital Image Processing*, Addison-Wesley Publishing Company, 1992.