Overview of Ubicomp Research Based on Scientific Publications

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Abstract. *This paper provides an overview and analysis of recent ubiquitous computing research performed internationally and in Brazil. The contributions are twofold. First, we extracted useful information from a dataset of papers published in top conferences focused on ubicomp, for instance, representativeness of authors and institutions, and communities' formation. Second, we analyzed all papers published between 2010 and 2011 in all top international conferences, creating a taxonomy of recent ubicomp research performed internationally. Next, we mapped SBCUP papers on this taxonomy. With that, we were able to compare the international and national research.*

1. Introduction

The future world envisioned by Weiser, called Ubiquitous Computing (ubicomp or pervasive computing), consider a computing environment in which each person is continually interacting with many wireless interconnected devices[Weiser 1993].

As a good research area, ubicomp gave us more questions than answers [Weiser et al. 1999], and many of them we still open [Caceres and Friday 2012]. There are many researchers around the world working on the ubicomp challenges, including Brazilians. Today we have three notable international conferences[1] (TOPint) devoted primarily to the area: Ubicomp[2](the oldest in its 14th edition), Pervasive[3], and Percom[4]. The national event dedicated to this field is SBCUP[5], which is in its 4th edition.

Ubicomp community, not only in Brazil, is in its infancy. In this case is natural to have many newcomers on this community. With that in mind, this paper provides an overview of recent ubicomp research internationally and in Brazil.

The contributions of this work are twofold. First, we collected information about all the papers published in all considered conferences and performed a data mining process extracting statistics like: most productive authors and institutions. We also analyzed the collaboration among authors identifying, for instance, communities' formation. Second, we analyzed all papers published in 2010 and 2011 in the TOPint group, creating a taxonomy of recent ubicomp research. We used this taxonomy also to discuss the research being performed in Brazil, by analyzing SBCUP papers.

The rest of this work is organized as follows: in Section 2 are described the related work. In Section 3 we present statistics about authors, papers and institutions. In Section 4 is discussed the representativeness of authors, and institutions. In Section 5 is presented an

[1]Based on the conference ranking maintained by Microsoft: http://academic.research.microsoft.com
[2]International Conference on Ubiquitous Computing
[3]International Conference on Pervasive Computing
[4]International Conference on Pervasive Computing and Communications
[5]Simpósio Brasileiro de Computação Ubíqua e Pervasiva

analysis of the authors' collaboration network. The taxonomy of recent research in ubicomp performed internationally and nationally are presented and discussed in Section 6. Finally, in Section 7 we conclude the paper.

2. Related work

Related to the first part of our work (statistics, and analysis) we can cite the following studies. In [Maia et al. 2012] the authors collected all data provided by all papers published between 1983 and 2012 in the SBRC[6]. With that dataset they built an authors' collaboration network, and performed analysis using complex network metrics. [Procópio et al. 2011] and [Freire and Figueiredo 2011] also built, and analyzed a collaboration network. The first one consider authors from SBBD[7]. Besides applying complex network metrics, they also presented some statistics about this conference. The second one consider two collaboration networks, global (composed by all authors that published in a paper listed in DBLP) and Brazilian (subset of the previous network, composed only by authors from Brazil). Besides the characterization of basic information on those networks, they created a metric, called ranking, which was used to measure the importance of individuals, as well as, groups.

Regarding to the second part of our work (taxonomy of recent research), the closest studied, as far as we know, is [Satyanarayanan 2001]. In this paper the author shows, through a taxonomy, how research problems in pervasive computing relate to those in mobile computing and distributed systems. Our taxonomy differs from this one, because it is concerned to present research being published recently in top events. As presented in Section 6, many problems presented in [Satyanarayanan 2001] are being studied today, for instance, energy-aware, and location sensitivity systems.

3. Ubicomp in numbers

This section first presents the dataset used throughout this work and several statistics for the considered conferences.

3.1. Dataset

We collected all articles (published in the main track only, not including, for example, demos) published in all editions Ubicomp, Pervasive, Percom (group named TOPint), and SBCUP, from the first edition until the edition conducted in 2011. For each paper we collected: title, year of publication, authors, and their respective institutions with its localization.

We are not considering the SBCUP dataset in all statistics and analysis performed, because sometimes it does not make much sense due to its small size.

3.2. Analysis of publications

Authors published 397 papers in thirteen editions of Ubicomp, 308 papers in nine editions of Percom and 203 papers in nine editions of Pervasive. Totalizing 908 papers and 2239 unique authors. In the universe of those authors, 1954 authors only publish in one of the three conferences, 256 authors published in two conferences and 26 published in all of them. In SBCUP we have 41 papers and 103 unique authors (77% in just one edition).

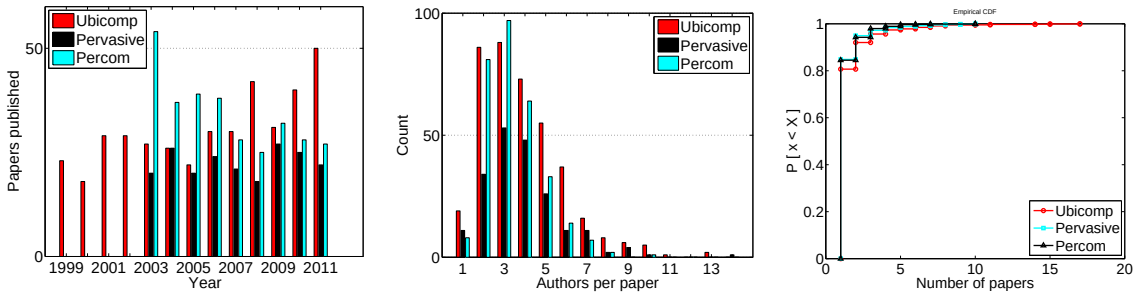
Percom, Pervasive and Ubicomp published by year an average (and the corresponding standard deviation σ) of 34 (σ =9), 22 (σ =3) and 30 (σ =8,78) papers respectively, SBUCP

[6]Brazilian Symposium on Computer Networks and Distributed Systems
[7]Simpósio Brasileiro de Banco de Dados

published 14 papers on average. Figure 1(a) shows the evolution of published paper in the TOPint group. Percom decreased from 54 to 27 papers in the last year. On the other hand, Ubicomp increased from 23 in 1999 to 50 papers published in 2011. Pervasive keeps stable in almost all editions, the maximum was 27 published papers in 2008.

Figure 1(b) shows that almost 50% of papers published was written by two or three authors (439 of 908 papers). The number of single authors has been decreased over the years. In fact, after 2006 any of the conferences had more than one single author per year. Ubicomp holds the record of number of authors per papers with two papers with 13 authors.

The CDF of the number papers per authors in the TOPint group is presented in the Figure 1(c). We can see that around 80% of authors published only 1 paper in all conferences, 98% of the authors published at most 5 papers, 0,013% published between 6 and 10 papers and 0,007% published more than 10 papers. The top 3 publishers in the TOPint group are Gregory D. Abowd, Anind K. Dey and Shwetak Patel with 27, 21 and 21 papers published respectively. In SBCUP the top 3 are: Adenauer Yamin (8), Cláudio Geyer (7), and Eduardo Nakamura (5).



(a) Publications per year (b) Authors per Paper (c) Publications per author

Figure 1. Percom, Pervasive and Ubicomp in Numbers

Considering all publications from the TOPint group, most of publications come from USA (20%), and from the second until the fifth positions we have, respectively, UK (5.4%), Germany (3.6%), Japan (2.3%), and Switzerland (2.3%). Brazil is the unique country of Latin America, with just 1 paper. A curious fact is that the only Brazilian author (first author of a paper published in 2011 at Ubicomp conference), does not have ubiquitous computing as his main research area.

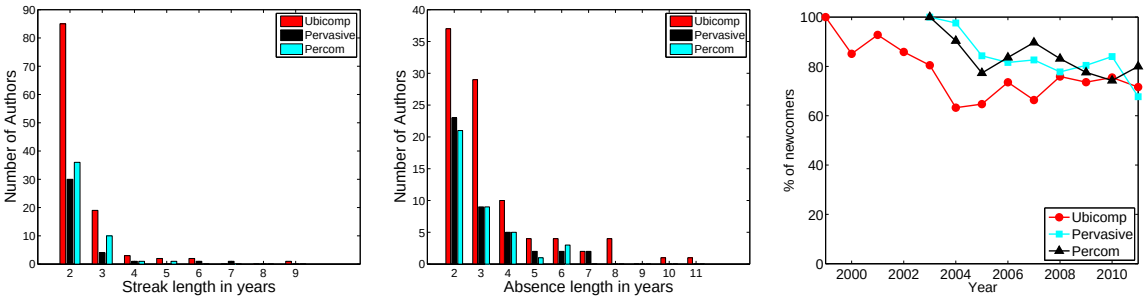
3.3. Analysis of Authors

TOPint group has a total of 2548 authors distributed as follows: 1103 in the Ubicomp; 613 in the Pervasive; and 832 in the Percom. However, some authors have published in more than one conference, then we have a number of 2239 distinct authors.

Anind K. Dey, Gregory D. Abowd and Shwetak Patel have presence highlighted in Ubicomp, each one has at least one article published in 9 editions of Ubicomp. Another interesting fact is that Shwetak Patel has 9 consecutive actuations (at least one publication in an edition) in the Ubicomp. Gregory D. Abowd has the largest number of actuations in editions of Pervasive (7), all consecutive, followed by Gaetano Borriello, Gerhard Troster, and Shwetak Patel (each one with 6 actuations). In Percom, Lionel Ni has the largest number of actuations (7 editions). It is interesting to note that Lionel Ni has no involvement in the Ubicomp or Pervasive, and the top publishers of these conferences do not have published in

Percom (except, Gerhard Troster with 1 paper in 2010). Among the top publishers Abowd and Patel have twelve joint publications, Abowd and Dey have two joint publications.

In Figure 2(a) is presented the number of authors by their streak length of actuations by years. We can see that most of authors published a maximum of 2 years in a row. This is in accordance with the information observed in the Figure 1(c) (most authors publish just one paper). In Figure 2(b) we can consider the longest period of absence of actuations, that is, the maximal period between two actuations in which no article was published. We can see that most of returning authors have a maximum of absence of 2 years.



(a) Uninterrupted (b) Absence (c) Newcomers

Figure 2. Authors actuation

The percentage of newcomers per year is displayed in Figure 2(c). Obviously, in the first edition of a conference the percentage of newcomers is 100%. Observing the Figure 2(c), we can see that in every edition of the considered events there are, at least, 63% of newcomers. This indicate that the number of returning authors is small, as we could observe previously in Sections 3.3 and 3.2. There are many conjectures for this fact, one of them is that there are few people that dedicate most of their time to research ubiquitous computing issues. Most of the authors might have their main research in other related areas, like Artificial Intelligence, and eventually work in some ubiquitous computing problems.

4. Representativeness of authors and institutions

The Figure 3 displays the authors 3(a) and institutions 3(b) by their number of occurrence in papers published in one of the three top international conferences (authors and institutions are counted just once by paper). We can see in the Figure 3(a) that the author Gregory D. Abowd is the one that published most papers. In the Figure 3(b) we can see, for instance, that Univ. of California, Univ. of Washington, and Intel are one of the most productive institutions in the area. In SBCUP the region south (highlights: UFRGS, UCPel, Unisinos, UFSM) and north (highlights: UFAM, and FUCAPI) have a strong participation (top authors mentioned in Section 3.2 belong to this groups).

The Figure 4 displays the institutions according to their number of occurrence in papers (institutions are counted just once in each paper), considering Ubicomp, Pervasive and Percom individually (figures 4(a), 4(b), 4(c) respectively). We can see that the most productive institutions showed in Figure 3 (considering all conferences), are not necessarily the most productive when we consider all conferences individually. Analyzing the results, it is possible to perceive a stronger correlation between top institutions from Ubicomp and Pervasive, than top institutions from Percom. For example, Univ. of Washington is one of the most productive institutions in the Ubicomp and Pervasive conferences, but considering Percom this is not the case. In Percom one of the most productive institutions is Hong Kong

(a) Cloud of authors (b) Cloud of institutions

Figure 3. Representativeness of authors and institutions

University of Science and Technology, but it is not on Ubicomp and Pervasive. This might be an indication that Ubicomp and Pervasive tend to accept studies in more similar areas.

(a) Ubicomp (b) Pervasive (c) Percom

Figure 4. Representativeness of institutions by conferences

5. Collaboration network

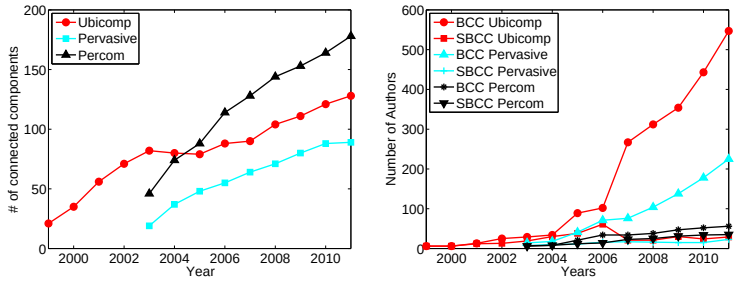
A natural process when researching is the formation of groups and establishment of partnerships (e.g., by affinity) in order to improve a work, or share experiences. Regarding to that, we identified the main institutions that performed collaboration with each other, in all TOPint group. Ubicomp has 40% of papers with collaboration (with involvement of more than one institution), Pervasive has 38% of papers with collaboration and has Percom 32% of papers with collaboration.

In the rest of this section we represented the scientific collaboration network of the TOPint group as a graph. In this graph nodes represent authors of papers, while the edges between two nodes indicates that there was a jointly publication between the authors. In Section 5.1 we discuss the connected components, and in Section 5.2 we identify some communities of authors.

5.1. Connected components

The Figure 5(a) presents the number of connected components evolution over the years of the TOPint group. In the first edition of Ubicomp, Pervasive, and Percom the network had 21, 19, 46 connected components, where each component are composed by a subset of authors of the network. After 5 editions, Ubicomp, Pervasive, and Percom had 80, 71, and 144 authors respectively (increasing 280%, 273%, and 213% respectively). In the last edition, Ubicomp, Pervasive, and Percom had respectively: 128, 89, 178 components (increasing 60%, 25%, 23% respectively). With that, we can observe that the number of components increase significantly more in the first years. We can also observe that the number of components found in Percom is much higher than Ubicomp and Pervasive.

In the Figure 5(b) we can observe the evolution of the biggest connected component (BCC), and the second biggest connected component (SBCC), of all networks (TOPint



(a) Number of components (b) Size of biggest component

Figure 5. Connected components

group). It is possible to see that by a certain number of editions the BCC starts to increase much more than the SBCC, for Ubicomp and Pervasive networks. This not true for the Percom network, where the BCC not increased significantly in any edition. Authors that were supposed to increase BCC may end up increasing the number of new components (as we can see in the Figure 5(a)).

5.2. Communities Visualization

One of the most relevant characteristics of graphs representing real systems is the structures of community. For the identification of communities we have grouped the final network (total) of the TOPint group, and used the algorithm k-clique community (the implementation is based in [Palla et al. 2005]). A community is defined as the union of all clicks of size k that can be reached through k-cliques adjacent (two k-cliques are considered adjacent if they share $k-1$ nodes).

The Figure 6 shows the visualization of communities with members assigned to universities. If an author was affiliated to more than one institution throughout its history, it was considered all affiliations recorded. We found 66 communities (using $k = 3$). Figure 6 shows only the 4 biggest communities identified (29, 16, 14, 12 authors respectively), due to space limitations. The size of the word indicates its popularity within their community. That is, in Figure 6(a) (biggest community) authors from the University of Washington, and Intel are very popular in this community.

(a) 29 authors (b) 16 authors (c) 14 authors (d) 12 authors

Figure 6. Four biggest communities - visualization by universities

6. Recent research in ubicomp - taxonomy

In order to provide a snapshot of the research being developed in the Ubicomp field, we analyzed (reading abstract, introduction, conclusion, and in particular cases other sections) studies published in 2010 and 2011 in the TOPint group. The analyzed studies were able to give us an overview of the actual research in the area, enabling the creation of a taxonomy about that. We do not have the pretension to say that we offer a complete recent research vision. But, since the events considered are representative of the area, we do believe it is

a good approximation about recent research topics. This taxonomy is very useful for two reasons. First, guide novices in the field. Second, it can be used to compare and discuss the ubicomp research performed in Brazil.

We identified seven categories (presented in the Figure 7), named: Context-aware, Privacy/Security, Innovative Technology, Invisible Computing, HCI Evaluation, Software Design, and Resource Limitation. Sometimes a paper can belong to one or more categories, but we take into account its main contribution, so we just mention the work in the dominant category. Categories have subcategories. They have been created if we identified at least 3 papers related to a "specialization" of the category. This is a way to highlight topics that is receiving considerable attention, which could indicate a research trend or a hot topic. The Figure 7 also offer the number of paper found in each category, for example, the category Invisible Computing has 23 papers (from these 23 papers 15 were classified in a subcategory, which means that the remaining 8 papers were not sub-categorized).

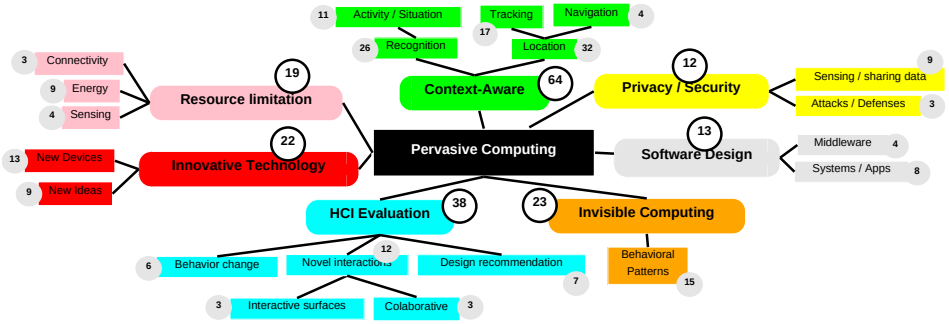


Figure 7. Taxonomy of recent research in ubicomp - Top international conferences

The following sections describe all categories of the taxonomy. Due to space limitation we did not cite all papers analyzed.

6.1. Context-Aware

This category groups studies that use context in order to automatically adapt a service behavior according to the actual context, for example environmental conditions or location. This is a very active and important field in pervasive computing, with a considerable number of studies (64). Some papers have been classified in two subcategories:

A-Recognition: This category groups works that derive high level context information from raw data (provided by sensors). This action is called recognition, interpretation or inference. The total of papers of this subcategory is 26. Some of them have been classified in a specific subcategory:

A.1-Activity: Here are grouped studies dedicated to recognize physical human activities.

B-Location: Location is a powerful context, which is accessible with mobile devices through, for instance, embedded GPS. This context enables a big range of new services. The number of papers classified in this subcategory is: 32. Some of them have been classified in two other subcategories:

B.1-Tracking: Here are grouped works that study tracking of mobile entities, which is a fundamental building block for location-based services.

B.2-Navigation: This subcategory is composed of studies that focus on methods and

techniques to help user's navigation.

6.2. HCI Evaluation

This category of studies presents investigations of the use of new, or existing Ubicomp technologies envisioning help the design and deployment of future Ubicomp applications, devices or systems. This is a relevant and very active field in Ubicomp area, we can see that by the number of papers found: 38. We have categorized some papers in three subcategories:

A-Behavioral Change: This subcategory is composed by studies that propose and/or evaluate mechanisms to provide user behavior change (e.g. make healthier meal choices).

B-Design Recommendation: Here are grouped works that are focused on providing guidance and recommendations in designing or deploying pervasive technologies.

C-Novel Interactions: This subcategory groups studies that propose or evaluate new types of interaction (e.g., touch interaction). The total of papers classified in this subcategory is 12. Some studies have been classified in two others subcategories:

C.1-Interactive Surfaces: Here are grouped studies related to interactive surfaces. They merge input and output into a single space, enabling designers to go beyond simple touch interactions, to integrate physical objects as interactive tools on the surface.

C.2-Collaborative: This subcategory is composed of papers that enable interaction of people to create and share context on pervasive devices.

6.3. Invisible Computing

Invisible computing is essential to the ubicomp visions, and is related to technologies that require users' minimal interaction. This section is composed to studies dedicated to this challenge. We classified 23 papers in this category. Some of them have been classified in a specific subcategory, named: Behavioral Patterns.

A-Behavioral patterns: in order to achieve invisible computing a fundamental step is understand people or systems behavioral patterns. The papers in this subcategory focus mainly on users' behavioral patterns identification, modeling, and prediction.

6.4. Innovative Technology

We would like to clarify that every work listed in this paper present innovation in its field. The category "Innovative Technology" is composed by studies that focus mainly on original devices or visionary conceptual ideas for ubiquitous computing. All the studies identified in this category (22 papers) were able to be categorized in two groups:

A-New Devices: This group of work presents the design of novel devices. Usually the new device is presented through a prototype.

B-New Ideas: This category is composed of work that presents new ideas that do not demand necessarily the design of new devices.

6.5. Resource Limitation

This category is composed by studies that focus mainly in deal with common resource limitations present in many ubicomp devices, like smart-phones. The total number of studies found in this category is: 19. Some of them have been classified in three subcategory:

A-Energy: The group of studies in this subcategory is mainly concerned in present new techniques to improve energy savings, and analysis of energy-related issues.

B-Connectivity: In certain situations the service my lack continuous network connectivity, for example in mobile environment. This is the main issue of this group of work.

C-Sensing: Previously difficult to observe process by one single device, due to its limited sensing capability coverage, becomes more feasible when other people collaborate with their devices (e.g., sensor-enabled cell phones). In this category were found only works related to participatory sensing [Lane et al. 2008], but this same category could be appropriated to group studied related to opportunistic sensing [Lane et al. 2008].

6.6. Privacy/Security

Today there are many possibilities to create, store and transmit several kinds of sensed data including GPS location, videos, photos, and so on. This brings new types of services, and also many challenges related to privacy and security of those personal data. We are able to classify all work in this category (12 papers) in two subcategories:

A-Sensing/sharing data: The sensing of personal data is possible using, for example, smart-phones, or smart environments (e.g. the tracking of energy consumption by a smart grid system). Increasing the amount of data stored or/and transmitted through the Internet, or other networks, increases also the need for securing the privacy of this data [Stajano 2004]. Studies grouped here are concerned with these issues.

B-Attacks / Defenses: This category is composed of studies that are more concerned with proposition or discussion of attacks and defense methods to personal data.

6.7. Software Design

This category is composed by studies that focus on pervasive software design (e.g, models). Total of papers of this category: 13. Some of them have been classified in two subcategories:

A-Middlewares: Here are grouped studies that are focused in provide and discuss middleware or frameworks to easy the development of pervasive systems.

B-Systems/Apps: This subcategory has studies concerned mainly in present pervasive applications or systems.

6.8. Ubicomp research in Brazil

In this section we present the classification of studies published in the SBCUP between 2010, and 2011 (Figure 8) in the proposed taxonomy (presented in Section 6). As we can see in the Figure 8, the most representative category is Software Design (52% of all papers), and the second one is Context-aware (with 19% of all papers). In the classification performed for international studies, presented in the Section 6, the most representative category is context-aware (35% of all papers), and the second one is HCI evaluation (20% of all papers). It is worth noting that we have not been able to classify studies in the category HCI Evaluation considering papers from SBCUP. Another relevant observation is that, in some categories, like in Invisible Computing, we did not find enough papers to create subcategories previously identified. We believe that these observations might be interesting for two reasons. First, there are many opportunities for Brazilians researchers acting in related fields, like HCI, or Security, to start addressing new issues brought by ubicomp, for instance, development and evaluation of new ways of user interaction. Second, guide newcomers to start his/her research in less explored areas.

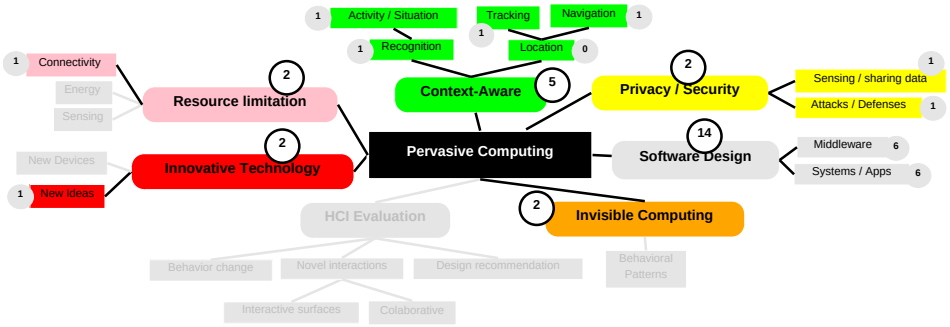


Figure 8. Taxonomy of recent research in ubicomp - Top national conference

7. Conclusions

In this work was presented an overview and analysis of recent ubicomp research. Through datasets of top conferences in ubicomp we showed relevant information, as representativeness of authors and institutions, and communities formed by authors. Analyzing all papers published in the TOPint group we proposed a taxonomy of recent ubicomp research, and discussed the national research in ubicomp. We believe that this work is very useful for newcomers in this field. As a future work is interesting to keep analyzing recent papers in the field to maintain the taxonomy updated.

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