Pervasive Grids
Challenges and Opportunities

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Abstract

Pervasive Grid is motivated by the advances in Grid technologies and the proliferation of pervasive systems, and is leading to the emergence of a new generation of applications that use pervasive and ambient information as an integral part to manage, control, adapt and optimize. However, the inherent scale and complexity of Pervasive Grid systems fundamentally impact how applications are formulated, deployed and managed, and presents significant challenges that permeate all aspects of systems software stack. In this paper, we present some use-cases of Pervasive Grids and highlight their opportunities and challenges. We then present why semantic knowledge and autonomic mechanisms are seen as foundations for conceptual and implementation solutions that can address these challenges.

Key words: Pervasive Grids, Grid Computing, Pervasive Systems

1 Introduction

Grid computing has emerged as the dominant paradigm for wide-area distributed computing [42]. The goal of the original Grid concept is to combine resources spanning many organizations into virtual organizations that can more effectively solve important scientific, engineering, business and government problems. Over the last decade, significant resources and research efforts have been devoted towards making this vision a reality and have lead to the development and deployment of a number of Grid infrastructures targeting a variety of applications.

However, recent technical advances in computing and communication technologies and associated cost dynamics are rapidly enabling a ubiquitous and pervasive world - one in which the everyday objects that surround us have

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embedded computing and communication capabilities and form a seamless Grid of information and interactions. As these technologies weave themselves into the fabrics of everyday life [55], they have the potential of fundamentally redefining the nature of applications and how they interact with and use information. This is leading to a new revolution in the original Grid concept and the realization of a Pervasive Grid vision. The Pervasive Grid vision is driven by the advances in Grid technologies and the proliferation of pervasive systems, and seamlessly integrates sensing/actuating instruments and devices together with classical high performance systems as part of a common framework that offers the best immersion of users and applications in the global environment. This is, in turn, leading to the emergence of a new generation of applications that use pervasive and ambient information as an integral part to manage, control, adapt and optimize [45,34,8,41]. These include a range of application areas including crisis management, homeland security, personal healthcare, predicting and managing natural phenomenon, monitoring and managing engineering systems, optimizing business processes, etc [7].

Note that it is reasonable to argue that in concept, the vision of Pervasive Grids was inherent in the visions of "computing as a utility" originally by Corbat et al [14] and later by Foster et al [20]. In this sense, Pervasive Grids are the next significant step towards realizing the metaphor of the power grid. Furthermore, while, Foster et al., defined a computational Grid in [18] as "... a hardware and software infrastructure that provides dependable, consistent, pervasive, and inexpensive access to high-end computational capabilities", the term pervasive in this definition refers to the transparent access to resources rather than the nature of the resources themselves. Pervasive Grids focus on the latter and essentially address an extreme generalization of Grid concept where the resources are pervasive and include devices, services, information, etc.

The goal of this position paper is to introduce the vision of Pervasive Grid computing and to highlight its opportunities and challenges. In this paper we first described the nature of applications in a Pervasive Grid and outline their requirements. We then describe key research challenges, and motivate semantic knowledge and autonomic mechanisms as the foundations for conceptual and implementation solutions that can address these challenges.

2 Pervasive Grid Applications and their Requirements

The applications enabled by Pervasive Grid systems can be classified along three broad axes based on their programming and runtime requirements. Opportunistic applications can discover and use available pervasive information and resources, to potentially adapt, optimize, improve QoS, provide a better user experience, etc. For example, a navigation system may use real-time traffic information (possibly obtained from other vehicles) to reduce or avoid congested routes. Similarly, a vehicle safety system may use information from oncoming vehicles to appropriately warn the driver of possible hazards. A key characteristic of these applications is that they do not depend on the availability of the information, but can opportunistically use information if it is available. Note that this application may consume raw information and process it locally. Alternately, they may “outsource” the processing of information using available resources at the source of the information or within the pervasive environment.

While the above applications are centered on a single user, in cooperative applications, multiple application entities (possibly wireless devices) cooperate with each other, each providing partial information, to make collective decisions in an autonomous manner. An example is a swarm of wireless robotic devices cooperatively exploring a disaster site or a group of cars sharing information to estimate the overall traffic situation. Finally, certain control applications provide autonomic control capabilities using actuation devices in addition to sensors, for example, a car may anticipate traffic/road conditions and appropriately apply the brakes. As an illustration consider the somewhat futuristic use-case scenario presented below that describes how an international medical emergency may be handled using the “anytime-anywhere” access to information and services provided by a Pervasive Grid.

Mr. Smith lives in Toulouse, France, and leaves for a few days to Vienna, Austria. Unfortunately, on the way, he is involved in an accident leaving him lying unconscious on the road. When help arrives, they only find a single piece of information on Mr. Smith, i.e., a numerical identifier (for example on a smart card), which allows the helps to quickly access Mr. Smith’s medical file (which is at least partially in France, perhaps in Toulouse), to find important information (for example, details of drug allergies, of its operational antecedents - was already anesthetized, with which product? did he have an operation? are there records available such as an operation report or x-rays?) that will allow the responders to adapt and customize the care given to Mr. Smith.

Let us consider this use-case in detail. First, let us assume (unrealistically) that the problem of the single identifier is solved (this particular point is a subject political, ethical, and is far from being solved, even at the European scale), and that Mr. Smith has a health card that encodes his identifier. Pervasive sensors are already embedded with Mr. Smith to monitor his blood pressure and sugar rate in his blood. These data are available through a specific application available for a range of devices (Palm, notebooks, ...) and transmitted via WiFi from the sensors to the application devices. Further, Mr. Smith’s medical data is distributed across various medical centers. The contents of the medical files must be accessible in a protected way: Only authorized individuals should be able to access relevant parts of the file, and ideally these authorizations are given by Mr. Smith himself. Note that all the documents would be naturally be in French and possibly in different formats and modalities.

Now, the Austrian responder, who only speaks German, has a Palm, with WiFi connection. The WiFi hot spot is in the ambulance and allows the responder to consult patient medical records through a public hospital network. The intervention by the responder begins on the spot of the accident and continues on the road towards the hospital. Please note that at this stage, the responder has no idea of the pervasive presence of the sensors embedded with Mr. Smith. When the responder wants to access information about allergies to certain medication, he should initially know where this information resides. From both the identifier of Mr. Smith and the request itself (allergies?), the system seeks the storage centers likely to have some information about Mr. Smith. The responder contacts these centers. He also needs to obtain authorization to enter the French information systems, which he obtains by starting from his certificate of membership to the health Austrian system. Trust certificates are established to allow him to access the network of care where the required data are.

An integration service must transform the responder's request to be compatible with the schema of the databases containing the relevant information, and negotiates, according to his profile and of the presented request, the parts of the database accessible to him. The request is expressed using a common vocabulary and semantic (ontology of the medical field) representation to get around the language issue.

To reach the data itself, the responder presents the mandatory certificates to read the files. Mr. Smith must have previously created certificates for standard accesses to some of his data, for example, the people being able to endorse the responders role can access information about drug allergies. A repository of the standard certificates for Mr. Smith must be accessible on line. The responder presents the retrieved certificates which authorizes the access and returns the data.

After this interaction, two kinds of information are available: First, the system alerts the responder of the presence of sensors with Mr. Smith, and starts the download of the appropriate application (graphic and language interface must be adapted) on its Palm. Thanks to the retrieved information, the responder know the sugar rate in the blood.

The second kind of information are related to the medical records of Mr. Smith. The metadata of the documents are analyzed to know their nature and to see how they can be exploited by the Palm. An adaptation service is probably required, to create a chain of transformation from the original documents (in written and spoken French) into documents that can be used by the responder currently in the moving ambulance, where he can only read and not listen (due to the noisy environment). Appropriate services include a service for audio-to-text transformation, a French-German translation service, etc. Finally, the first-aid worker gets the relevant data and administers the appropriate medication to the patient.

During the transportation, information about patient (drugs, known allergies, identifier of the patient) are transmitted to the hospital. In the hospital, even before the arrival of the ambulance, a surgeon can recover, using similar mechanisms but with different conditions (less constrained terminal, higher role in the care network, etc.), more complete information (operational antecedents, scanner, etc.) in order to be able to intervene appropriately. The surgeon can decide to start some more complex computation on the data he retrieved like comparing this patient characteristics (and data, such as images, analysis, etc.) to a patient database to better suit this particular patient case and provide personalized help. This may lead to use utility computing facilities on a stable infrastructure.

In the scenario, the responder is very active, interacting with the local sensors and the global infrastructure. One should understand that much of the tasks should be automated, delegated and performed transparently by his device.

The pervasive grid ecosystem, which integrates computers, networks, data archives, instruments, observatories, experiments, and embedded sensors and actuators, is also enabling new paradigms in science and engineering - ones that are information/data-driven and that symbiotically and opportunistically combines computations, experiments, observations, and real-time information to understand and manage natural and engineering systems. For example, an Instrumented Oil-Field can (theoretically) achieve efficient and robust control and management of diverse subsurface and near subsurface geo-systems by completing the symbiotic feedback loop between measured data and a set of computational models, and can provide efficient, cost-effective and environmentally safe production of oil reservoirs. Similar strategies can be applied to CO2 sequestration, contaminated site cleanup, bio-landfill optimization, aquifer management and fossil fuel production.

Another example application is the modeling and understanding of complex marine and coastal phenomena, and the associated management and decision making processes. This involves an observational assessment of the present state, and a scientific understanding of the processes that will evolve the state into the future, and requires combining surface remote sensing mechanisms (satellites, radar) and spatially distributed in situ subsurface sensing mechanisms to provide a well sampled blueprint of the ocean, and coupling this real-time date with modern distributed computational models and experiments. Such a pervasive information-driven approach is essential to address important national and global challenges such as (1) safe and efficient navigation and marine operations, (2) efficient oil and hazardous material spill trajectory prediction and clean up, (3) monitoring, predicting and mitigating coastal hazards, (4) military operations, (5) search and rescue, and (6) prediction of harmful algal blooms, hypoxic conditions, and other ecosystem or water quality phenomena. For example, underwater and aerial robots and oceanic observatories can provide real-time data which, coupled with online satellite, radar and historical data, advanced models and computational and data-management systems, can be used to predict and track extreme weather and coastal behavior, manage atmospheric pollutants and water contaminants (oil spills), perform underwater surveillance, study coastal changes, track hydrothermal plumes (black smokers), and study the evolution of marine organisms and microbes.

An area where a pervasive grids can potentially impact in a dramatic way is crisis management and response where immediate and intelligent responses to a rapidly changing situation could mean the difference between life and death for people caught up in a terrorist or other crisis situation. For example, a prototype disaster response test bed, which combines information and data feeds from an actual evolving crisis event with a realistic simulation framework (where the on-going event data are continually and dynamically integrated with the on-line simulations), can provide the ability for decision support and crisis management of real situations as well as more effective training of first-responders. Similarly, one can conceive of a fire management application where computational models use streaming information from sensors embedded in the building along with real time and predicted weather information (temperature, wind speed and direction, humidity) and archived history data to predict the spread of the fire and to guide firefighters, warning of potential threats (blowback if a door is opened) and indicating most effective options. This information can also be used to control actuators in the building to manage the fire and reduce damage.

3 Crosscutting Challenges

The Pervasive Grid environment is inherently large, heterogeneous and dynamic, globally aggregating large numbers of independent computing and communication resources, data stores, instruments and sensing/actuating devices. The result is an unprecedented level of uncertainty that is manifested in all aspects of the Pervasive Grid: System, Information and Application [40,48]. System uncertainty reflects in its structure (e.g., flat, hierarchical, P2P, etc.), in the dynamism of its components (entities may enter, move or leave independently and frequently), in the heterogeneity of its components (their connectivity, reliability, capabilities, cost, etc.), in the lack of guarantees, and more importantly, in the lack of common knowledge of numbers, locations, capacities, availabilities and protocols used by its constituents. Information uncertainty is manifested in its quality, availability, compliance with common understanding and semantics, as well the trust in its source.

Finally, application uncertainty is due to the scale of the applications, the dynamism in application behaviors, and the dynamism in its compositions, couplings and interactions (services may connect to others on a dynamic and opportunistic way).

The scale, complexity, heterogeneity, and dynamism of Pervasive Grid environments and the resulting uncertainty present thus requires that the underlying technologies, infrastructures and applications must be able to detect and dynamically respond during execution to changes in the state of execution environment, the state and requirements of the application and the overall context of the applications. This requirement suggests that [40]: (1) Applications should be composed from discrete, self-managing components which incorporate separate specifications for all of functional, non-functional and interaction-coordination behaviors. (2) The specifications of computational (functional) behaviors, interaction and coordination behaviors and non-functional behaviors (e.g. performance, fault detection and recovery, etc.) should be separated so that their combinations are composable. (3) The interface definitions of these components should be separated from their implementations to enable heterogeneous components to interact and to enable dynamic selection of components.

Given these features, a Pervasive Grid application requiring a given set of computational behaviors may be integrated with different interaction and coordination models or languages (and vice versa) and different specifications for non-functional behaviors such as fault recovery and QoS to address the dynamism and heterogeneity of the application and the underlying environments.

4 Research Opportunities in Pervasive Grid Computing

We believe that addressing the challenges outlined above requires new paradigm for realizing the Pervasive Grid Infrastructure and its technologies that is founded on semantic knowledge and autonomic mechanisms [40,48]. Specifically, (1) static (defined at the time of instantiation) application requirements, system and application behaviors to be relaxed, (2) the behaviors of elements and applications to be sensitive to the dynamic state of the system and the changing requirements of the application and to be able to adapt to these changes at runtime, (3) common knowledge to be expressed semantically (ontology and taxonomy) rather than in terms of names, addresses and identifiers, and (4) the core enabling middleware services (e.g., discovery, coordination, messaging, security) to be driven by such a semantic knowledge. Further the implementations of these services must be resilient and must scalably support asynchronous and decoupled behaviors. Key research challenges includes:

Programming Models, Abstractions and Systems: Applications targeted to emerging Pervasive Grids must be able to address high levels of uncertainty inherent in these environments, and require the ability to discover, query, interact with, and control instrumented physical systems using semantically meaningful abstractions. As a result, they require appropriate programming models and systems that support notions of dynamic space-time context, as well as enable applications capable of correctly and consistently adapting their behaviors, interactions and compositions in real time in response to dynamic data and application/system state, while satisfying real time, functional, performance, reliability, security, and quality of service constraints. Furthermore, since these behaviors and adaptations are context dependent, they need to be specified separately and at runtime, and must consistently and correctly orchestrate appropriate mechanisms provided by the application components to achieve autonomic management.

Data/Information Quality/Uncertainty Management: A key issue in pervasive systems is the characterization of the quality of information and the need of estimating its uncertainty, so that it can effectively drive the decision making process. This includes algorithms and mechanisms to synthesize actionable information with dynamic qualities and properties from streams of data from the physical environment, and address issues of data quality assurance, statistical synthesis and hypotheses testing, and in-network data assimilation, spatial and/or temporal multiplexing, clustering and event detection. Another related aspect is providing mechanisms for adapting the level and frequency of sensing based on this information. Achieving this in an online and in-network manner (as opposed to post-processing stored data) with strict space-time constraints presents significant challenges, which are not address by most existing systems. Note that, since different in-network data processing algorithms will have different cost/performance behaviors, strategies for adaptive management of tradeoffs so as to optimize overall application requirements are required.

Systems Software and Runtime & Middleware Services: Runtime execution and middleware services have to be extended to support context-/content-/location-aware and dynamic, data-/ knowledge-driven and time-constrained executions, adaptations, interactions, compositions of application elements and services, while guaranteeing reliable and resilient execution and/or predictable and controllable performances. Furthermore, data acquisition, assimilation and transport services have to support seamless acquisition of data from varied, distributed and possibly unreliable data sources, while addressing stringent real-time, space and data quality constraints. Similarly, messaging and coordination services must support content-based scalable and asynchronous interactions with different service qualities and guarantees. Finally, sensor system management techniques are required for the dynamic management of sensor systems including capacity and energy aware topology management, runtime management including adaptations for computation/communication/power tradeoffs, dynamic load-balancing, and sensor/actuator system adaptations.

5 Related Work

5.1 Current Grid Computing Research Landscape

Grid computing research efforts over the last decade can be broadly divided into efforts addressing the realization of virtual organizations and those addressing the development of Grid applications. The former set of efforts have focused on the definition and implementation of the core services that enable the specification, construction, operation and management of virtual organizations and instantiation of virtual machines that are the execution environments of Grid applications. Services include (1) security services to enable the establishment of secure relationships between a large number of dynamically created subjects and across a range of administrative domains, each with its own local security policy, (2) resource discovery services to enable discovery of hardware, software and information resources across the Grid, (3) resource management services to provide uniform and scalable mechanisms for naming and locating remote resources, support the initial registration/discovery and ongoing monitoring of resources, and incorporate these resources into applications, (4) job management services to enable the creation, scheduling, deletion, suspension, resumption, and synchronization of jobs, (5) data management services to enable accessing, managing, and transferring of data, and providing support for replica management and data filtering. Efforts in this class include Globus [1], Unicore [4], Condor [53] and Legion [25]. Other efforts in this class include the development of common APIs, toolkits and portals that provide high-level uniform and pervasive access to these services. These efforts include the Grid Application Toolkit (GAT) [6], DVC [51] and the Commodity Grid Kits (CoG Kits) [32]. These systems often incorporate programming models or capabilities for utilizing programs written in some distributed programming model. For example, Legion implements an object-oriented programming model, while Globus provides a capability for executing programs utilizing message passing.

The second class of research efforts deals with the formulation, programming and management of Grid applications. These efforts build on the Grid implementation services and focus on programming models, languages, tools and frameworks, and application runtime environments. Research efforts in this class include GrADS [10], GridRPC [37], GridMPI [27], Harness [36], Satin/IBIS [39] [38], XCAT [23] [30], Alua [54], G2 [29], J-Grid [33], Triana [52], and ICENI [21].

These systems have essentially built on, combined and extended existing models for parallel and distributed computing. For example, GridRPC extends the traditional RPC model to address system dynamism. It builds on Grid system services to combines resource discovery, authentication/authorization, resource allocation and task scheduling to remote invocations. Similarly, Harness and GridMPI build on the message passing parallel computing model, Satin supports divide-and-conquer parallelism on top of the IBIS communication system. GrADS builds on the object model and uses reconfigurable object and performance contracts to address Grid dynamics, XCAT and Alua extend the component based model. G2, J-Grid, Triana and ICENI build on various service based models. G2 builds on .Net [3], J-Grid builds on Jini [2] and current implementations of Tirana and ICENI build on JXTA [5]. While this is natural, it also implies that these systems implicitly inherit the assumptions and abstractions that underlie the programming models of the systems upon which they are based and thus in turn inherit their assumptions, capabilities and limitations.

Most of these works do not deal with all the specificities of Pervasive Grids. We now detail some works in that specific directions.

5.2 Pervasive Grid Efforts

Davies, Storz and Friday [49,50] were among the first to introduce the concept of “Ubiquitous Grid”, that is close to our Pervasive Grid vision. The purpose of their article is to compare the notion of Grid Computing (definition of I. Foster [19]) and the notion of Pervasive Systems (definition of M. Weiser [55]). They identify similar interests : heterogeneity, interoperability, scalability, adaptability and fault tolerance, resources management, services composition, discovery, security, communication, audit, payment. They then briefly present a use-case for a ubiquitous Grid, which they develop using Globus Toolkit 3 (GT3). Lack of details makes it difficult to evaluate exactly what has been done to make GT3 behave as a an ubiquitous Grid, and what aspects of ubiquity has been addressed.

Hingne et al. [26] propose a multi-agent approach to realize a P-Grid. They are primarily interested in communication, heterogeneity, discovery and services composition, and scheduling of tasks between the different devices constituting the P-Grid.

McKnight et al. [35] introduce the concept of a Wireless Grid. Their interest is in the mobile and nomadic issues, which they compare with traditional computing Grids, P2P networks and web services. An interesting aspect of this article is that it investigates the relationships between these actors. In the article, the authors focus on services that they identify as the most important, i.e., resources description and discovery, coordination, trust management and access control.

In [47], S.H. Srinivasan details a Wireless Pervasive Grid architecture. The author separates Grid in two parts: the "backbone grid", physically linked and analogous to network backbones, and the wireless "access grid". Agents realize the proxy between the two grids, and act on behalf of mobile devices in the "access grid" on the "backbone grid". Interesting aspects of this effort are the pro-activity and context-awareness of the presentation to end-users.

Coulson et al. [16] present a middleware structured using a lightweight runtime component model (OpenCom) that enables appropriate profiles to be configured on a wide rage of device types, and facilitates runtime reconfiguration (as required to adapt to dynamic environments).

More recently, Coronato and De Pietro [15] describe MiPEG, a middleware consisting of a set of services (compliant to grid standard OGSA) enhancing classic Grid environments (namely the Globus Toolkit) with mechanisms for handling mobility, context-awareness, users' session and distribution of tasks on the users' computing facilities.

Complementary to these, existing research efforts have tackled aspects of integrating pervasive systems with computing Grids, primarily mobility and adaptation. Research presented in [6,24,22] have focused on the use of light devices to interact with computing Grids, e.g., submitting jobs and visualizing results. A closer integration of mobile devices with the Grids is addressed in [44,43], which proposes proxy services to distribute and organize jobs among a pool of light devices. The research presented in [31] solicits surrounding devices to participate in a problem solving environment. Others efforts such as [46,28] are interested in the advantages of mobility features of IPv6 in the notification and adaptation of Grids. Mobile agents are used in [11,9] to migrate objects between sites. Some researchers [12,13] have investigated how a Grid middleware (Legion, OGSI.NET) can be adapted to tackle mobility issues. Context-awareness is the primary focus of the effort presented in [56], while the authors in [17] include mobility and context-awareness in their approach.

6 Summary

The proliferation of pervasive sensing/actuating devices coupled with advances in computing and communication technologies are rapidly enabling the next revolution in Grid computing - the emergence of Pervasive Grids. This, in turn, is enabling a new generation of application that use pervasive information and services to manage, control, adapt and optimize natural and engineering real-world systems. However, the inherent scale and complexity of Pervasive Grid systems fundamentally impact the nature of applications and how they are formulated, deployed and managed, and presents significant challenges that permeate all aspects of systems software stack from applications to programming models and systems to middleware and runtime services. This paper outlined the vision of Pervasive Grid Computing along with its opportunities and challenges, and presented a research agenda for enabling this vision.

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