A Service-oriented Framework for Developing Personalized Patient Care Plans for COVID-19

Abeer Elahraf
Rutgers University
Newark, NJ, USA
aelahraf@newark.rutgers.edu

Ayesha Afzal
Air University
Multan, Punjab, Pakistan
ayesha@aumc.edu.pk

Ahmed Akhtar
Lahore University of Management Sciences
Lahore, Punjab, Pakistan
16030059@lums.edu.pk

Basit Shafiq
Lahore University of Management Sciences
Lahore, Punjab, Pakistan
basit@lums.edu.pk

Jaideep Vaidya
Rutgers University
Newark, NJ, USA
jsvaidya@rutgers.edu

ABSTRACT

The COVID-19 pandemic has identified weaknesses and stresses in the existing healthcare and governance system, even in the most developed countries. Given the scale and scope of the pandemic, existing healthcare systems are heavily resource constrained, and home-based isolation has been considered as a potential first step for reducing both the disease spread and the stress on the healthcare system. However, the needs and requirements of home-based isolation are extremely unique for each patient, depending on their medical condition and comorbidities, family responsibilities, and environmental constraints. Therefore, it is necessary to develop personalized patient care plans to ensure that the needs of each patient are appropriately met. In this paper we propose a service oriented framework that allows dynamic composition and management of such plans assuming existence of an appropriate knowledge base and availability of web-services interfaces of the underlying systems of caregivers and service providers. We develop a prototype implementation to show the feasibility of the proposed framework and discuss the challenges/issues in deploying such a system in practice.

KEYWORDS

Personalized patient care plans, Interoperability, Knowledge-centric workflows, Web services

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1 INTRODUCTION

The COVID-19 pandemic is an unprecedented event in the recent history that has affected the entire globe. In the absence of vaccines, physical distancing, intensive contact tracing, and case isolation are considered as the most effective measures to control COVID-19 outbreak [26]. Healthcare facilities all over the world are overwhelmed by the sudden influx of COVID-19 patients and are running out of both space and resources to take care of existing and incoming patients. Therefore, it is important to keep the non-critical COVID-19 patients in self-isolation at home but still provide them with proper care.

For effective management of home-based isolation, patient care should not be limited to the illness but should also take into account other factors that are related to the needs and sustenance of patients and their dependents. For example, some of the common factors identified for non-adherence of self-isolation include: lack of financial compensation [12], lack of support for child care in a single parent family [29], comorbidities that require regular medical support outside home care [25], perceptions about impact on mental health [33]. As an example, consider a patient with a chronic kidney disease who requires dialysis once a week. Furthermore, suppose that this patient is a single mother with dependent children. Care for such a patient under self-isolation at home may require: delivery of required medicines, food and other necessities for the patient and dependents, transportation arrangement for the dialysis visit, home sample collection by trained staff for relevant laboratory tests, regular visits by a nurse, remote monitoring of patient condition, etc.

A personalized patient care plan is essential to coordinate and guide the care activities for COVID affected individuals. Traditionally, the patient care plan is developed by and implemented in collaboration with the patient, family members, caregivers, and service providers to ensure consistent and coordinated delivery of care while considering the patient's condition, needs and preferences. Ongoing review of the care plan is an essential requirement in order to support the care team to revisit patient's health care goals and to cater for the patient's evolving needs, preferences and the treatment responses to interventions [18].

Table 1: Home Patient Care Systems and Services

Category	Available Systems/Services
Clinical information systems	NHS Care Connect Open APIs†, Google Cloud Healthcare†, Allscripts API for EHR integration‡, HiPaaS‡, Trella Health for healthcare analytics‡,
Home health providers and Telehealth systems	Acurata Triage Scheduling Solution‡, BetterRX and Doxy.me‡, GetWellNetwork‡, MatrixCare by ResMed‡, Citus Health‡, Home Health (infection prevention for home care and hospice)‡, Transcend Strategy Group Solution for remote alerts and communication‡
Vital Signs Monitoring	Current Health's Automated Wearable Vital Signs Monitoring & Alert Escalation‡, iHealth‡, ManageBGL: Cloud-based diabetes management platform‡, Fitbit activity tracker API‡ ‡
Emergency Transportation	Select Ambulance‡, Ambulance Messaging - HL7 API†, Uber Health‡
Pharmacy	Walgreens Pharmacy Prescription Refill†, CVS Pharmacy API†, H-E-B Refill Rx‡, Truepill API‡
Laboratory Testing	Covid-Rapid API†, TridentCare Portable X-Ray and Ultrasound Services‡
Food Delivery	Uber Eats‡, GrubHub‡

§ Open source systems, † Publicly available Web services, ‡ Publicly available commercial systems

A patient care plan can be considered as a structured workflow of different activities that require interaction between the different healthcare information systems, such as clinical information systems, e-pharmacy systems, laboratory testing services, remote patient monitoring services [1]. To support care delivery to patients under self-isolation at home, patient care plans need to be extended by integrating with the systems and applications of other service providers such as food delivery services, medical transportation services, etc. Services computing provides the key enabling technology to enable coordination and information exchange among the applications and systems of caregivers and service providers for composition and management of personalized patient care plans.

Table 1 shows some of the available healthcare information systems and relevant home care applications. All these systems and applications provide web service-based interfaces to enable their integration into processes and workflows. There are also open service-based APIs for wearable devices that can be used for the purpose of remote patient monitoring (e.g., heart rate, blood pressure, blood glucose levels, etc.). However, there is no unified system that supports automatic interfacing with the operational systems of caregivers/ service providers for development, real-time monitoring, and management of such care plans.

In this paper, we address precisely this problem. We propose an integrated framework that enables dynamic composition and management of personalized patient care plans. This integrated framework extends prior work on dynamic composition of emergency response processes, and applies to the COVID-19 context [16]. Our primary objective is to demonstrate the feasibility of such an approach for creating personalized patient care plans, specifically for COVID-19 patients. The proposed framework assumes that all of the requisite underlying services are available through web service based interfaces and an appropriate knowledge base exists and is encoded in the form of an ontology with reasoning support.

The care plan is composed by selecting the appropriate patient care activities and integrating the systems and web service APIs of provider organizations, as depicted in Figure 1. We employ ontology-based reasoning to determine the standard care activities for the given patient and identify the relevant service providers and APIs of their operational systems by taking into account the patient's pre-existing medical conditions and contextual knowledge e.g., patient's location and preferences. The discovered web service APIs of identified service providers are then used to generate an executable care plan that is continuously monitored and updated and recomposed based on the patient's evolving needs, preferences and the treatment responses to interventions.

The remainder of this article is organized as follows. Section 2 provides the problem statement. Section 3 presents the proposed approach. Section 4 presents a prototype implementation of the proposed framework. Section 5 discusses the system-level technology and policy issues that need to be addressed to deploy such a system in the real-world. Section 6 presents a review of related work. Finally, Section 7 concludes the paper and discusses future work directions.

2 PROBLEM STATEMENT

We address the problem of developing personalized care plans for COVID-19 patients under home isolation based on their medical conditions, needs, and requirements. The care plans are developed by integrating the web services of the relevant caregivers and service providers into an executable workflow, which is dynamically instantiated for each individual patient for remote monitoring and care delivery. We state the problem as follows:

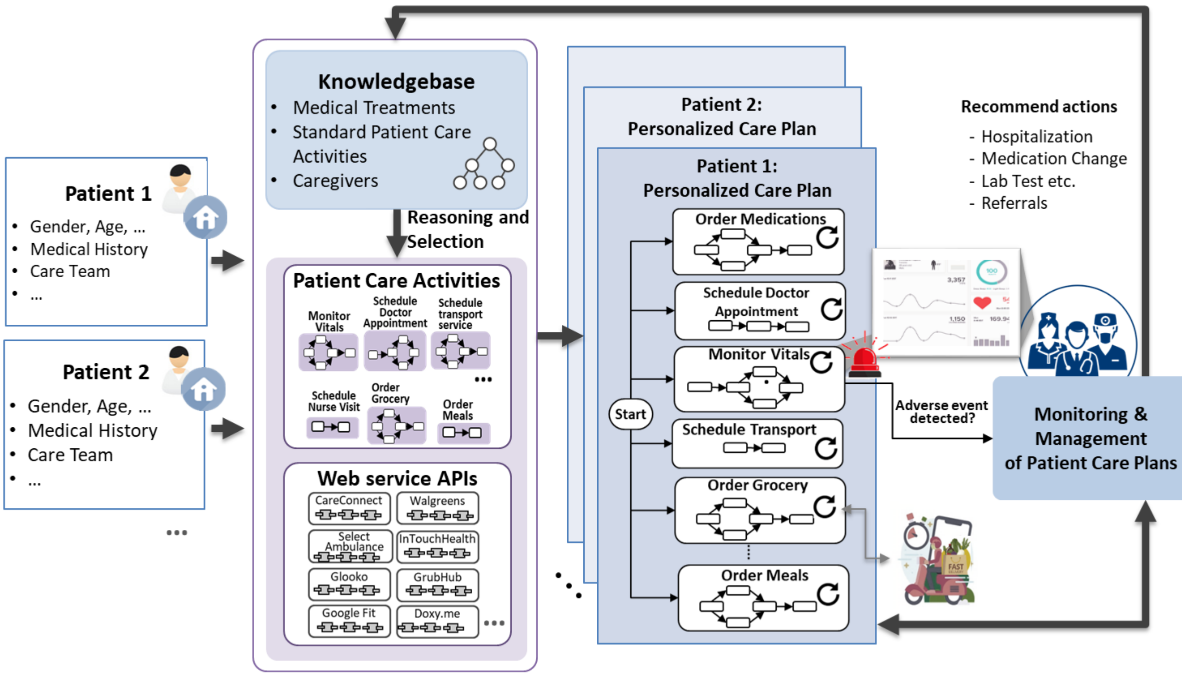

Figure 1: Framework for management of personalized patient care plans

Given:

- *Individual patient information, including personal details and medical condition;*
- *Ontology, including: i) standard care activities for different medical conditions, ii) types of caregivers and service providers in relation to the standard care activities; iii) resources required for the different standard care activities;*
- *available web services/APIs of the operational systems of caregivers and service providers.*

Develop and instantiate a personalized care plan by creating a workflow of the relevant care activities and mapping the appropriate web services to these activities. Develop a monitoring infrastructure that can dynamically adapt and evolve the instantiated plan based on changes in the patient's medical condition and the environmental context.

3 PROPOSED APPROACH

The proposed framework for dynamic composition of a patient care plan employs a multi-step approach that incrementally generates an executable care plan and enables adaptability to the evolving care requirements of the patient. Figure 1 depicts the architectural view of our proposed framework. This framework relies on an ontology for the healthcare environment and employs rule-based reasoning to dynamically develop a personalized care plan for a given patient. The ontology includes standard care activities characterized by medical conditions (both pre-existing and evolving). In addition, the ontology includes the categories of caregivers and service providers involved in patient care in a home setting. Rule-based reasoning is employed to identify the required care activities based on the given patient's information (personal details and medical conditions). Appropriate APIs of the operational systems of caregivers and service providers are discovered considering the contextual knowledge (e.g., patient's location, vital's monitoring devices, insurance service, and meal preferences, etc.). The standard care activities are encoded in the ontology as *abstract process fragments* which are essentially structured workflows of activities that need to be performed for required care/service delivery. For example, for a diabetic patient with chronic kidney disease who is under self-isolation at home, the standard care activities may include scheduling of weekly telehealth appointments, patient's vitals monitoring, medication refill requests to the pharmacy, transportation scheduling for weekly dialysis visits, and scheduling of meals delivery based on patient's dietary needs, etc. Given the care activities and the operational systems/ service APIs of the service providers identified from the ontology, an abstract workflow of the care plan is generated to support care delivery. The workflow details the interaction among the operational systems of involved service providers required to provide patient care. Now, the abstract workflow needs to be converted into a concrete execution plan. Essentially, an execution order of identified care activities is determined and binding of each activity to appropriate operational systems and services is performed in this step. First, we employ a reachability analysis based service composition approach for generating an executable care plan. Then, executable process code (e.g., in BPEL language) is generated for deployment and instantiation of the care plan on a process execution engine.

Patient care plans require continuous monitoring for any changes in patient's health conditions and evaluating the patient's response

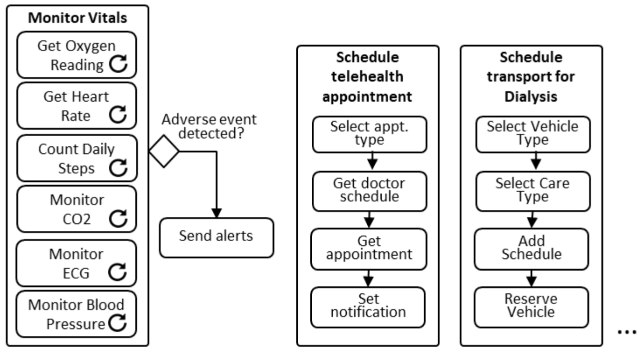

Figure 2: Examples of some of the standard care activities for a self-isolated COVID-19 patient requiring weekly dialysis

to treatment and progress. To address this, our proposed framework includes a care plan monitoring and management component that updates the care plan whenever any new events are triggered as a result of a change in patient's conditions or the care team's decisions.

In the following subsections, we discuss the steps in the proposed system in detail.

3.1 Ontology and reasoning support

The patient care ontology includes (i) standard care activities for different types of medical conditions such as kidney disease, hypertension, cancer, asthma, hypertension, liver disease and thalassemia, etc. Each standard care activity has associated types of caregivers and service providers, and required resources.

Standard Care Activities are high-level workflows of care activities modeled as abstract process fragments. We represent these activities in the standard Business Process Model and Notation (BPMN). Figure 2 shows an example abstract process fragment of standard care activities for a self-isolated COVID-19 patient with a chronic kidney disease condition. Note that the activities are only defined at an abstract level and lack any information about the specific operational systems for communication and coordination with the caregivers and service providers involved in care delivery.

Service provider represents a caregiver organization (e.g., local health department, home health agency, non-government/private home health care organization), or any other service provider organization/ individual that is directly or indirectly involved in patient care activities. A service provider has properties including, name, service-type, and location, as well as the links to their operational systems/ web services APIs (WSDL files). These APIs can be used to query the internal databases and operational systems of the service provider for resource request, information sharing, and service delivery.

Care activities selection and service discovery: Given the patient's profile information (including patient's personal details, medical conditions, location, vitals monitoring device information, insurance service, and transportation and meal preferences, etc.) and care team's input, required care activities are identified through ontology reasoning. In addition, ontology reasoning is employed to identify appropriate caregivers and service providers and discover the APIs of their operational systems. Note that the standard care activities are only abstract process fragments. The activities in the abstract process fragment are realized through composition of web services that provide an interface to the service providers' operational systems.

Given the selected care activities and APIs of the identified service provider systems, the next step is to compose a care plan that enables the care delivery by enabling interaction and seamless integration of heterogeneous systems of the involved service providers as discussed below.

3.2 Care Plan Composition

Care plan composition involves elaborating the standard care activities identified for the patient into a concrete process. As discussed earlier, the standard care activities are only abstract workflows of activities, which lack information about their execution order and the specific operational systems of service providers for the execution of these activities. In order to compose a concrete process, we employ a reachability analysis based approach that determines the execution order of the care activities and bind these activities to appropriate operational systems and service APIs.

The general state reachability analysis problem is modeled as a 3-tuple $\langle I, A, G \rangle$ where I denotes the initial state, A denotes a set of available actions and G denotes the goal state [21]. Initial state is constituted by a set of propositions representing the initial conditions of the problem. Goal state contains a set of propositions (called problem goals). A given state consists of a set of facts. Set A consists of the actions that can be used to modify system states. Each action $a \in A$ has some preconditions denoted as prec(a) and an effect if the action is taken. The effect of an action a consists of the set of additional predicates that are evaluated to be true in the successor state (denoted by add(a)) and the set of existing predicates that are evaluated to be false and removed from the successor state (denoted by del(a)). Note that the set of predicates in add(a) and del(a) do not overlap. An action $a \in A$ is applicable to a state s if preconditions of a are satisfied by s. If an action a is applied to a state s, then the successor state s' is computed as s' $=s-\text{del}(a) \cup \text{add}(a)$. The output of the reachability analysis problem is a sequence of actions, which, if applied to the initial state I, leads to a state s such that $s \subseteq G$ [21].

In the context of care plan composition, we model the set of selected web service operations as a set of available actions denoted by the set A. Specifically, we model each web service operation as an available action and determine its preconditions and effects by extracting the input and output attributes from the service's description (available in WSDL). We compute the *initial state* (I) of the composition problem from the patient's profile attributes and user inputs; the *goal state* (G) is computed from the expected outputs of selected care activities.

Example 3.1, detailed below, illustrates our care plan composition approach.

Example 3.1. Consider the example of the self-isolation patient with a chronic kidney disease discussed in Section 1. Based on the patient's profile information and user inputs, we first compute the initial state of the process composition problem. Figure 3(a) shows

```
Initial State:{
"Required Activities":
   "Remote Patient Monitoring",
   "Schedule Transport for Dialysis",
   "Schedule Telehealth Appointment",

"Gender": "Female",
"Location": "Paramus, NJ",
"Major Condition": "Kidney disease",
"Device Type": "Glucometer",…
}
```

Care Activity	Goal State Attributes
Monitor vitals:	`Temperature, Pulse rate, Systolic BP, Diastolic BP, Respiration rate, Blood Sugar, …`
Schedule transport for dialysis:	`Repeat Frequency, Start Date, End Date, Pickup Time, Vehicle ID, Contact Details, …`
Schedule telehealth appointment:	`Appt Start Date, Appt End Date, Time, Appt Type, Doctor ID, Doctor Name, …`

Figure 3: (a) Initial state computed from patient's profile attributes (b) Goal state computed from selected patient care activities

example attributes in the patient's profile considered in the initial state. To compute a goal state for the composition problem, we consider the system state after successful execution of care activities retrieved through ontology reasoning in Figure 2. Each of these activities has associated input and output attributes. For example, activity 'monitor vitals' requires patient's device information as input and returns patient's vitals including temperature, pulse rate, respiration rate, and blood sugar levels, etc. Similarly, the activity 'Schedule transport for dialysis' requires patient preferences as input and return scheduled vehicle information as output. The combined effect of the output attributes of these activities determine the goal state of the composition problem as shown Figure 3(b).

State reachability analysis of the formulated service composition problem determines an execution order of services that satisfies the composition goal. The service execution order thus obtained for the given activities is then used to construct the workflow of the required care plan as discussed in the following subsection.

3.3 Code generation, instantiation and execution

In this step, first, any control-flow dependencies between the different care activities are identified and a workflow is generated. Next, using the mapping information of each care activity to appropriate operational system/service API, executable process code of the developed workflow is generated e.g., in BPEL language. This executable process is then deployed on a process execution engine and instantiated and brought to execution in a runtime environment.

3.4 Monitoring and adaptation/evolution of care plan

A patient care plan is a dynamic, knowledge-driven process that adapts and evolves based on changes in the patient's health conditions, circumstances and collaborative decisions of the care team [19]. For example, patient's medication and care needs may change based on their symptoms and medical conditions. Our proposed framework supports continuous monitoring and reviewing of the instantiated care plan through continuous evaluation of patient's evolving needs, preferences, and treatment responses to interventions. Essentially, re-composition of the care plan is triggered whenever an adverse event is detected or when a a member of the care team initiates a change in care plan based on some clinical decisions. Technically, this requires performing ontology based reasoning to identify additional care activities to cater for the new requirements and invoking the process composition and code generation components for executable code generation and redeployment of the extended care plan. This care plan extension and re-composition are continued until the patient's health goals are satisfied.

4 PROTOTYPE IMPLEMENTATION

In this section, we provide a brief overview of the prototype system that we have developed to illustrate the functionality of the proposed framework.

We have developed an initial ontology for patient care activities and related caregiver/service provider classes in Ontology Web Language (OWL) for the prototype system. For reasoning and inference with the ontology, we used Apache's Jena inference subsystem [9]. The web-based application has been developed in Java (J2EE) and deployed on an Apache Tomcat web server. For deployment and execution of BPEL based care plans we have used Apache ODE workflow engine.

We demonstrate the functionality of the developed prototype system using the example of a COVID-19 patient with a chronic kidney disease condition as discussed in Section 1.

The user (a member of the patient's care team) is provided with a web-based interface that facilitates generation and management of a personalized care plan for an individual patient. The initial input to the system requires basic information about the patient and their pre-existing medical conditions as given in the patient's health record. This information may include patient's personal details, medical conditions, location, vital's monitoring device information, insurance service, as well as any transportation and meal preferences, etc. This information is provided either by the patients themselves or by their caregivers or healthcare providers. For our current prototype this information can be input through a web interface. In general, if the system were to be deployed in a practical care setting, it should be possible to link this system to the EHR system to automatically retrieve the requisite information. Based on the given information, the system recommends standard care activities as shown in Figure 4. A member of the care team (physician, nurse, etc.) can then review and select appropriate activities as per the patient's requirements (Figure 4-right panel). Based upon the decision and the information available in the ontology, the system identifies relevant service providers and the APIs of their

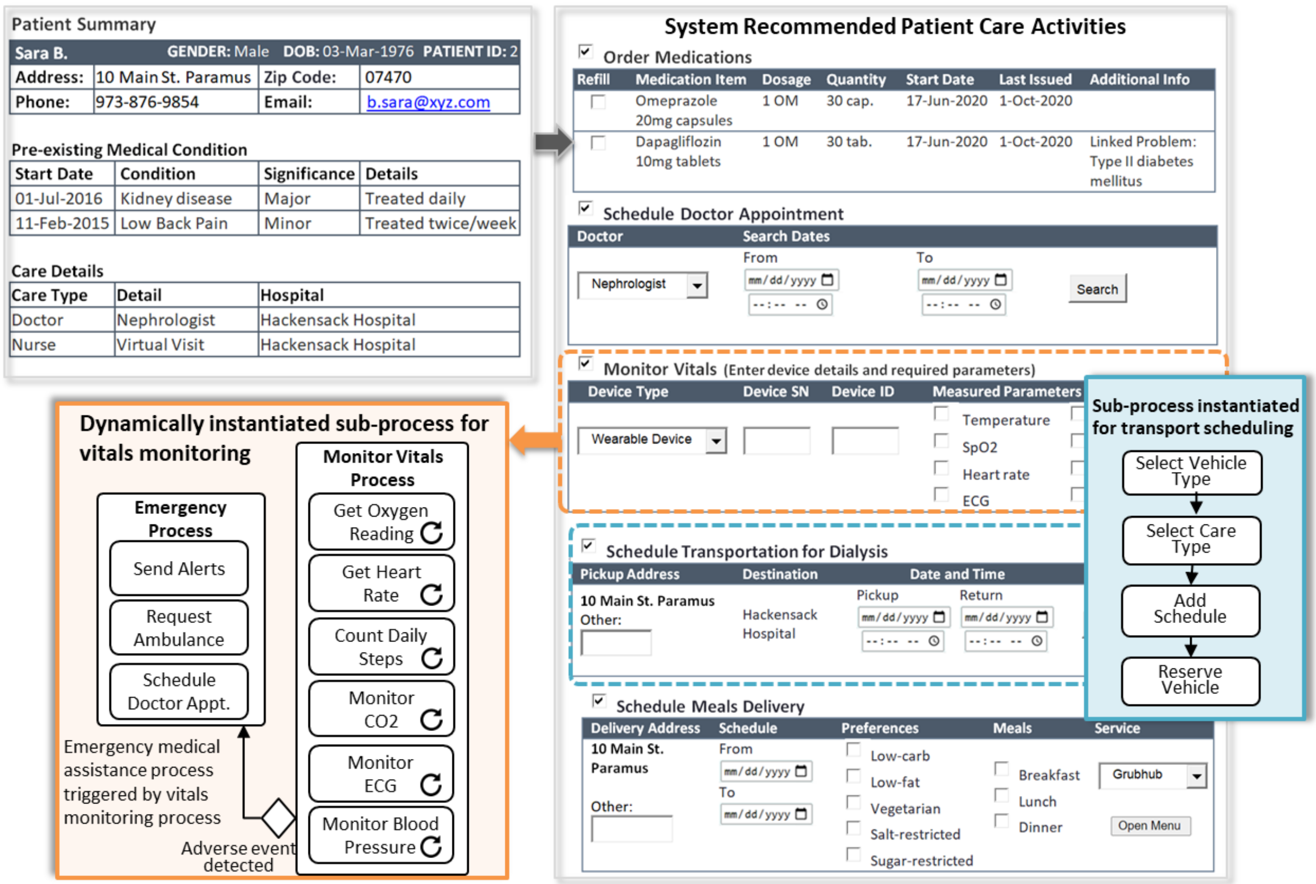

Figure 4: Prototype System Implementation

operational systems/ services for the execution of selected activities. Upon confirmation, a complete care plan is composed and deployed enabling interaction between the caregivers and service providers. The composed care plan consists of multiple sub-processes corresponding to the selected activities in the care plan as depicted in Figure 4 for vitals monitoring, transport scheduling sub-processes, etc.

We would like to emphasize that the system supports continuous monitoring of the care plan. This allows for re-assessment of patient's evolving needs, preferences and treatment responses to interventions and re-composition of the care plan as discussed in Section 3.4. Members of the patient's care team can remotely monitor the patient's conditions through a web interface and receive alerts whenever the patient outcomes deviate from the established goals of the care plan.

5 SYSTEM-LEVEL TECHNOLOGY AND POLICY ISSUES

Our prototype shows that it is indeed feasible to provide personalized at-home care for patients in the COVID-19 setting. In this section, we present the challenges/issues in realizing this vision in practice and then discuss the potential next steps from a technical and from a policy perspective. There are several technical and policy issues that need to be addressed to take this system beyond a prototype level for deployment in the real-world environment, which we discuss below:

Scalability: While it is easily possible for our prototype to develop personalized care plans for multiple patients, it essentially does so one at a time. This becomes problematic even when only a few thousand patients are considered, let alone scaling it to municipalities or larger administrative levels. One possibility is to parallelize the underlying infrastructure and utilize appropriate load balancing solutions. Architecting such solutions is a non-trivial technical exercise. Furthermore, given the overlap in terms of patient needs, environments, and situations, it ought to be possible to utilize the reasoning carried out in one care plan to another. Essentially, it should be possible to develop a system that can take multiple care plans, and appropriately split them into a set of non-overlapping components that can be individually reasoned, and then reassembled to provide complete care plans for a group of patients with similar attributes and medical conditions. This is a significant technical challenge. Finally, there is a degree of human supervision necessary in reviewing and making the final decisions on each of the personalized care plans, which can significantly increase the burden on the care team providers, especially when a multitude of plans need to be developed. It is also necessary to provide appropriate grouping/clustering solutions that can reduce the individual supervision necessary, which is another significant technical challenge.

Privacy and Security: Our current system assumes that there are no system level security or privacy issues. In practice, given that all of the underlying information used by the system is sensitive, and that there are multiple participants and organizations involved in the care plan, we need to ensure that all organizational access policies as well as individual and legislative privacy requirements are satisfied.

With respect to organizational security, there is prior work on collaborative access control[11, 23, 31] that can applied within this context. With respect to privacy, we currently assume that the system is deployed in a trusted curator setting, where the system entities looking at and operating over the data are indeed allowed to access the underlying information. If any broader insights are to be provided to policy makers, it should be possible to protect the underlying individual information through the use of privacy models such as differential privacy[15].

Interoperability and Standardization: Currently we assume that there is no semantic heterogeneity in terms of the data/information maintained by different organizational systems or the web service APIs. In general, this is not the case, and it is important to resolve heterogeneity issues before the different systems can interoperate in a seamless manner. One such initiative was undertaken by the US Department of Homeland Security (DHS) in the form of Unified Incident Command Decision Support (UICDS) system for adopting standards-based Service-Oriented Architecture (SOA) to enable government entities, critical infrastructure owners and operators, and other private organizations across the country to work together for an effective and coordinated response to emergencies and catastrophic situations [28, 30]. An alternative is to utilize a machine learning based approach to resolve heterogeneity across all the different collaborating systems, as proposed by [3].

Auditability: With a complex system consisting of multiple underlying systems, participants, and evolving environmental constraints, it is important to provide auditability to reduce the possibility of misuse/gamification and increase the confidence in using such a system. One possibility is to use a blockchain based decentralized approach that essentially records each decision along with the underlying justification including the provided input and interaction between the different collaborators. This can be recorded in the form of execution of the appropriate smart contract. Now, if a sequence of actions needs to be audited, the transaction log of each smart contract can be examined. Furthermore, by using a game-theoretic approach as proposed by [4], it is possible to minimize the cost of auditing while making the overall approach incentive compatible, thus enforcing no cheating for rational participants.

6 RELATED WORK

The use of medical ontologies and semantic reasoning has a rich history in the context of clinical decision support systems[10, 13, 32] and tele-medicine systems[20]. More recently, tele-medicine systems have also been used for managing the COVID-19 pandemic[22]. However, these systems have not been designed for a pandemic, which typically requires personalized care beyond the traditional hospital in-patient and out-patient settings. Furthermore, for effective management of home-based isolation which is necessary in a pandemic, patient care should not be limited to the illness but should also take into account other factors that are related to the needs and sustenance of patients and their dependents. This requires integration and interoperation among multiple systems including clinical decision support systems, telemedicine systems, as well as other non-medical systems such as emergency transportation, food delivery, etc. Currently, there does not exist any unified framework or system that enables information sharing and operation-level interoperability among these diverse systems for providing personalized care to COVID-19 patients under home isolation.

In the emergency management domain, Service-oriented approach has been successfully employed to establish interoperability and coordination among the applications and systems of collaborating organizations for emergency response planning and management. Examples od some service-oriented platforms and systems for interoperable information exchange for emergency management and response planning include: XchangeCore[1], formerly known as Unified Incident Command Decision Support System (UICDS) [28, 30], FEMA Incident Resource Inventory System (IRIS) [17], Service-Oriented ArchiteCtures Supporting Networks of Public Security (SoKNOS) [14], and social media alert and response to threats to citizens (Smart-C) [2]. However, this work has not yet been applied to the COVID-19 setting.

We note that patient care plans are essentially knowledge-driven processes with two main characteristics; (i) Unpredictable and emergent process workflow structure – The care activities and process structure are not predefined and determined dynamically depending on the case- and patient-specific information and doctor's / caregiver's recommendations and decisions; (ii) Care plan goals may change depending upon patient outcomes e.g., adverse event to certain medication may trigger the need to evaluate and update the care plan urgently. While there is a lack of integrated approaches for the composition and management of patient care plans, there are some existing works addressing the different general requirements in knowledge-driven workflow development in a piecemeal manner[5–8, 24, 27], which we hope to explore in the context of personalized care delivery.

7 CONCLUSION AND FUTURE WORK

In this paper we have studied the problem of creating personalized care plans for COVID-19 patients under home isolation. We propose a service oriented framework that allows for dynamic composition and management of personalized patient care plans assuming existence of an appropriate knowledge base and availability of web service based interfaces for interacting with the underlying systems. We develop a prototype to show the feasibility of the proposed framework and discuss the challenges/issues in deploying such a

[1]https://www.saberspace.org/xchangecore-home.html

system in practice. In the future, we plan to work on several of underlying technical challenges including scalability, security, privacy, interoperability, and auditability.

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