Leveraging object-orientation for real-time imaging systems

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Abstract

Imaging systems are traditionally developed using structured analysis and design techniques at best. Such approaches tend to be rigid with respect to changing needs, technologies, devices and algorithms—for example, when additional compression algorithms are needed or attached devices are changed large parts of software applications employing those techniques and interfacing with those devices must be modified to accommodate the change. In a larger perspective, these systems are difficult or impossible to reuse; each new problem requires a new solution.

This is generally undesirable and often not necessary, but only if best practices in software engineering are employed. These best practices have been explored and documented in detail with regard to object-oriented systems, which suggests that it is an appropriate paradigm to employ in the development of future imaging systems. This work examines these best practices, in the form of patterns and design principles, with reference to imaging systems and within the context of the Java imaging APIs.

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1. Introduction and previous work

The application of software engineering best practices in the development of real-time imaging systems appears to be an area in need of attention. The wider software engineering community is finally showing signs of maturity, as evidenced by improvements reported in the yearly Chaos Reports [1] but within that broad community there are still distinct pockets of engineers developing software systems with scant knowledge of, or adherence to, best practices. As Pereira points out “until recently the development of real-time systems was characterized as an ‘occult art’, where ‘ad hoc’ fashions and ‘programming from scratch’ techniques abounded” [2]. This is particularly problematic in application domains that experience continued advancement and evolution, such as real-time imaging. Developers of such systems are forced to re-design and re-write essentially the same system, but with slight modifications for the new application, algorithms or technologies employed. Function libraries exist that provide a plethora of image manipulation and transformation techniques for use here, but the underlying structure of each application often changes so little reuse is possible outside of these functions.

A more desirable alternative would be to tailor a general solution for each specific case, reusing as much

of the general case as possible and only redefining or adding the aspects that change. So, for example, if a new compression technique is required of a system, only the compression aspects of the general system are modified or extended and the rest of the application is unchanged. A development technique well-suited to this scenario is object-oriented analysis and design. Here the system is described as a set of classes that can be instantiated and work in cooperation with one another to fulfill the responsibilities of the application. While this is simply an alternate viewpoint of a software system, it allows the application of sophisticated principles and patterns that yield robust, maintainable, extensible and therefore reusable systems. In [3] the basic application of object-orientation (OO) to imaging systems was investigated and compared against the more traditionally adopted practice (at least in the imaging field [4]) of structured analysis, structured design. This paper extends that work by examining the processes and practices that can be employed within the auspices of object-orientation in the building of reusable frameworks for imaging systems.

2. OO and real-time

Before the benefits of object-oriented approaches can be examined, some long-discussed issues regarding the suitability of object-oriented implementations for

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real-time systems must be examined. The most obvious is the inefficiencies of OO languages. This is really a comment aimed at the interpreted nature of Java. There are really two issues here, however. First, real-time does not, and should not be thought of, as real-fast. Real-time applications may indeed have tight time constraints to meet, but most of all, real-time systems should be deterministic (and we will return to this issue shortly). Second, Java is only one of several OO languages. In situations where performance is key C++ may be more appropriate since it does not have Java's in-built garbage collection or interpretation. Another alternative is to utilize the real-time specification for Java [5].

Some more profound exceptions to OO were debated in a special section of Real-Time Systems journal [6] and included the "inheritance anomaly" and non-determinisms introduced by polymorphism and garbage collection.

2.1. Inheritance anomaly

The inheritance anomaly is the situation that arises when the introduction of a new method or the overriding of an inherited method in a subclass requires modification or redefinition of inherited properties. Synchronization inheritance anomalies are an extension of this concept where new constraints are imposed in inherited classes [7]. These anomalies are seen as problematic because they hinder the reuse of well-defined and verified real-time programs. There is a problem with this thinking, however. The assumption that inheriting features from a previously tested and trusted class obviates the need to test the new subclass is entirely flawed; each new context for an object offers new ways to misuse the object [8]. Beyond this naïve misunderstanding there is a more fundamental error, one common when inheritance is used as a convenient code reuse mechanism. Instances of derived classes should be substitutable for instances of their base classes [9], so must therefore be subtypes of the base class. Since a subtype cannot strengthen the pre-conditions of its supertype [10] the inheritance anomalies only occur when this central precept of OO is ignored.

Examining the example used by Bergmans and Aksit [7] it is clear where their problems arise. They describe how a Crane class that provides the basic functionality of a crane system has the additional abilities of storage and retrieval through its inheritance relationship with a BoundedBuffer class—an already questionable decision, since the basic heuristic for inheritance is whether the "is a" relationship holds and clearly the statement "a Crane is a BoundedBuffer" is not correct. They then discover that the BoundedBuffer behaviors must be constrained for real-time performance when used in the Crane, thus leading to modification of the inherited buffer features and the reported synchronization

inheritance anomalies. However, these additional constraints violate the substitutability of Crane and BoundedBuffer (Crane is no longer a subtype of BoundedBuffer) so it is not surprising that anomalies occur.

2.2. Non-determinism

Perhaps the most substantive concerns regarding the use of OO for real-time are the non-deterministic aspects of the implementations. Java utilizes a garbage collector for memory management and reclamation that can preempt any thread at any time. This clearly introduces a level of non-determinism that would hinder usefulness. However, the real-time specification for Java [5] introduces a memory model that allows objects to be allocated outside of the heap in a memory area that is not subject to the garbage collector. Furthermore, alternative OO languages exist, such as C++, that do not have an in-built garbage collector. In both cases memory management is left to the developer.

Of course there is still the issue of polymorphism and late binding, where method names are resolved at runtime. As will be evident in the later discussion, polymorphism is central to design for reuse so while we can avoid the late binding in some OO languages (class methods in C++ are bound at compile time, for example) that would somewhat defeat the purpose. This does not necessarily present a stumbling block, however. Polymorphism is used as a mechanism to avoid repeated conditional logic, to support future extension without modification, and to allow interfaces and their implementations to vary independently. In all of these cases even though the implementation is not known at compile time, the interface is and therefore the object type. Returning to the above discussion concerning substitutability of subtypes, we see that proper subtypes must conform to the supertype not only in signature, but in constraints, thus each polymorphic choice must adhere to the constraints imposed on the base class, including any specified temporal constraints. This is not enforced automatically, the burden is on the developer to ensure conformance, but this is also true for each branch in a switch statement in procedural languages.

3. Design for reuse

We see then, that the object-oriented paradigm is compatible with real-time requirements and can progress with the consideration of leveraging the properties of OO for building reusable systems. The key to reuse is the identification of the mutable and immutable services or responsibilities of a system and isolating them. This is typically achieved by building frameworks.

A framework can be loosely defined as a set of interfaces (or abstract classes) and concrete classes that

provide a stable set of core services to an application and can be extended for domain specific implementations through explicit extension mechanisms that isolate the variant aspects. Successful frameworks embody sincere distillations of core principles that underpin the object-oriented paradigm.

3.1. OO principles

When considering the benefits of object-oriented approaches to image processing applications it is easy to focus on the ideas of combining data and behavior into an encapsulated entity that better approximates the “things” in the problem domain and consider this closeness between reality and the modeling domain to be the central benefit of using objects. While this can be considered an advantage, the purported intuitiveness of the approach is, in fact, something of a fortuitous side effect. The real advantages of applying object-oriented paradigms are the future extensibility and reuse that can be attained, and the relative ease of future changes.

Several studies indicate that software systems are subject to near-continuous change: requirements change, merge, emerge, and mutate; target languages, platforms and architectures change; and most significantly the way the software is employed in practice changes [11]. This changeability places considerable burden on the software design. How can systems that must support such widespread change be built without compromising quality?

While object-oriented systems can be designed to be as rigid and resistant to extension and modification as in any other paradigm, OO has the ability to include distinct design elements that can cater to future changes and extensions. These “design patterns” were first introduced to the mainstream of software engineering practice by Gamma et al. [14]. The “Gang of Four (GoF)” patterns, as they are commonly known, are based upon key principles that have been recognized as supporting reuse.

3.1.1. Open closed principle (OCP)

First recorded by Meyer [10], OCP states that classes should be open to extension, but closed to modification. That is, it should be possible to extend the behavior of a class in response to new or changing requirements, but modification to the source code is not allowed. While these expectations may seem at odds, the key is abstraction. In OO a superclass can be created that is fixed, but can represent unbounded variation by subclassing.

3.1.2. Once and only once (OAOO)

While certainly not a new idea, Beck [12] put a name to the principle that any aspect of a software system—be it an algorithm, a set of constants, documentation, or

logic—should exist in only one place. This isolates future changes, makes the system easier to comprehend and maintain, and through the low coupling and high cohesion that the principle instills, the reuse potential of these aspects increases. The encapsulation of state and behavior in objects, and the ability to inherit properties between classes allows for the rigorous application of these ideas in an object-oriented system, but is difficult to implement in structured techniques.

3.1.3. Dependency inversion principle (DIP)

The DIP states that high-level modules should not depend upon low-level modules. Both should depend upon abstractions. Which can be restated as: abstractions should not depend upon details, details should depend upon abstractions. Martin [13] introduced this idea as an extension to OCP with reference to the proliferation of dependencies that exist between high- and low-level modules. For example, in a structured decomposition approach, the high-level procedures reference the lower level procedures, but changes often occur at the lowest levels. This infers that high-level modules or procedures that should be unaffected by such detailed modifications may be affected due to these dependencies. Again, consider the case where the camera characteristics change and even though perhaps only one routine needs to be rewritten, the calling module(s) need to be modified and recompiled as well. A preferable situation is to invert these dependencies such as is evident in the Liskov Substitution Principle.

3.1.4. Liskov substitution principle (LSP)

Liskov [9] expressed the principle of substitutivity of subclasses for their base classes as:

“If for each object O_1 of type S there is an object O_2 of type T such that for all programs P defined in terms of T , the behavior of P is unchanged when O_1 is substituted for O_2 then S is a subtype of T .”

This principle has led to the concept of type inheritance and is the basis of polymorphism in object-oriented systems, where instances of derived classes can be substituted for each other provided they fulfill the obligations of a common superclass.

3.1.5. Interface segregation principle (ISP)

ISP states that “many client specific interfaces are better than one general purpose interface” [13]. This is, in essence, an extension of the idea of separating a module’s interface from its implementation and therefore allowing them to vary independently. In cases where a class has many clients, designers should create specific interfaces for each client and multiply inherit them into the class. This approach ensures that any changes made to methods called by one client are not propagated to other clients with the payoff that those

unaffected clients do not need recompilation or redeployment.

3.2. Design patterns

While the principles detailed above describe desirable aspects of object-oriented systems their systemic nature restricts their appropriate application during design to experts. Less advanced developers need more prescriptive, specific examples of the ideas expressed in the principles and this has led to the development of design patterns. Unfortunately research has shown that most designers of imaging systems are in this category [3].

To disseminate the ideas expressed in the principles—robust, extensible, reusable software design—to the wider community Gamma et al. [14] developed a catalogue of design patterns. Each pattern addresses a common problem and then describes the core of the solution to that problem [15]. Many patterns languages, as they are termed, have since been created so most practitioners refer to Gamma's design patterns as the "Gang Of Four", or "GoF", patterns in recognition of the four authors.

There are 23 GoF patterns, too many to describe in detail here. Of interest to this work, however, is the appropriate application of these design patterns, usually in concert, to framework development in general, and imaging frameworks in particular. In subsequent sections two imaging frameworks will be examined for the presence of these patterns so those identified later will be described now.

3.2.1. Abstract factory

"Provide an interface for creating families of related or dependent objects without specifying their concrete classes." [14]

The abstract factory pattern is applied in situations where it is desirable to control the creation of instances in a system such that clients of those instances are only aware of their interfaces, not their implementations, and families of related objects are used together and this constraint must be enforced. Rather than have domain objects create other instances a factory is defined that is responsible for instantiation of products thus ensuring that related objects are of the same family (when manipulating GIF images, only GIF codec elements and data structures are created, and not some GIF elements and a JPEG quantization table, for example).

3.2.2. Singleton

"Ensure a class only has one instance, and provide a global point of access to it." [14]

The Singleton pattern is often used in conjunction with the Abstract Factory, as it is often desirable to have only one instance of a factory per family, but the pattern is applicable beyond this example. In many situations it is necessary to allow only one instance of a class to exist and a simple way to achieve this is to make the class responsible for maintaining its only instance by defining a static, or class, method that returns the instance if it already exists, otherwise creates it.

3.2.3. Observer

"Define a one-to-many dependency between objects so that when one object changes state, all its dependents are notified and updated automatically." [14]

In general the GoF patterns encourage low coupling and high cohesion within a design, and the Observer pattern is a prime example. If an object is interested in changes in another object (a subject) it could call the subjects accessor methods (*getSomething()*) periodically. This is undesirable, however, if many objects are similarly interested as it results in many couplings and the need for all those interested objects to know what information the subject maintains (its implementation). An alternative is to have the subject send updates to the interested objects, but ensuring that the subject equally does not know anything about the implementation of the interested observers. This is achieved by having observers implement an interface that the subject will use to call with updates, and having the subjects implement an interface that allows observers to subscribe (and unsubscribe) to those updates.

3.2.4. Façade

"Provide a unified interface to a set of interfaces in a subsystem. Façade defines a higher-level interface that makes the subsystem easier to use." [14]

Another pattern intended to reduce coupling is the Façade. This is used to limit the communication and dependencies between subsystems by eliminating direct couplings between objects in different subsystems. This is achieved by defining a façade object that provides a single simple access point to the services of the subsystem and directs incoming requests to the appropriate objects within the subsystem to fulfill those requests. This shields the implementation of a subsystem from its clients thus promoting reuse, isolating internal objects from change, and generally reducing complexity.

3.2.5. Strategy

“Define a family of algorithms, encapsulate each one, and make them interchangeable. Strategy lets the algorithm vary independently from clients that use it.”[14]

A central feature of OO already mentioned is the encapsulation of data and behavior in a single entity, which can be restated as giving entities the means to manipulate and transform their own state. This gives rise to a problem, however, if there are many variants to the transforms of an object. Either the variants must be chosen with conditional logic (which is static and problematic to maintain and extend) or the object is subclassed with one variant per subclass (which is also static and possibly counter-intuitive; a list can be sorted in many ways, but it is always the same list, not a *BubbleSortableList* or a *QuickSortableList*, etc.). In such cases the Strategy pattern can be applied where the variant algorithms are encapsulated in their own classes and each implements the same interface so that clients are only abstractly coupled to the algorithm. This results in process-oriented classes which seems to counter the original premise of OO, but better supports extension, maintenance and dynamic (runtime) change.

4. Imaging frameworks

Concrete examples of frameworks for imaging have been developed for the Java platform. Two of these, the Java Image I/O and 2D™ API's, will be investigated with reference to the patterns and principles of design. These are constituent packages of the Java Advanced Imaging (JAI) API that cannot be discussed in detail here given its considerable size and complexity—over 300 classes and interfaces are defined in the JAI API.

4.1. Java image I/O API

The Java Image I/O API is an example of a framework that provides a pluggable architecture for working with images stored in files and accessed across a network [16]. The API comprises six packages defining 46 classes and interfaces and supports extension through format-specific plugins created by subclassing core abstract classes, implementing defined interfaces and parameterizing subclasses with metadata. A partial class diagram of this API is presented in Fig. 1.

The notation used is from the Unified Modeling Language (UML) where classes are rendered as boxes with three partitions (for identity, attributes, and methods), interfaces are boxes with only two partitions (an interface does not have attributes), and relationships

are indicated with lines. Four types of relationship can be indicated:

- generalization (inheritance) using an a solid line with an open triangle at the superclass end,
- dependency using a dashed directed line pointing to the entity depended upon,
- realization (implementation of an interface) using a dashed line with an open triangle at the interface end, and
- association using a solid line with, optionally, a diamond at one end indicating composition in a whole-part association.

4.1.1. API description

The central class in this model is the *ImageIO* class. This provides a set of static convenience methods for locating and calling *ImageReaders* and *ImageWriters* and creating *ImageInputStreams* and *ImageOutputStreams*.

Images are represented in the API by the *BufferedImage* class. This is a subclass of the abstract class *java.awt.image* and comprises a *ColorModel* (an abstract class that encapsulates the methods for translating a pixel value to color components and an alpha component) and a *Raster* (an array of pixels). The *Raster* itself comprises a *SampleModel*, an abstract class that specifies the type of samples in the *Raster* and defines an interface for extracting these samples from an image.

The *BufferedImage* also inherits (termed “implements” in Java) the *WritableRenderedImage* interface which is a subclass of the *RenderedImage* interface. It is this *RenderedImage* interface that is required by the *ImageWriter* class, an abstract superclass responsible for image writing and encoding that implements the *ImageTranscoder* interface. Instances of *ImageWriter* subclasses (The API provides default *ImageWriter* subclasses for JPEG and PNG image formats) are instantiated by a service provider interface subclass of the *ImageWriterSpi* abstract class.

Another service provider subclass (of the *ImageReaderSpi* abstract class) is responsible for instantiating instances of *ImageReader* subclasses. *ImageReader* is an abstract superclass for decoding and reading image files and, like *ImageWriter*, has default subclasses for JPEG and PNG, and also for GIF.

The final aspect of the Image I/O API shown in Fig. 1 is the *EventListener* interfaces (*IIOWriteProgressListener*, *IIOReadProgressListener*, etc.). *ImageReader* and *ImageWriter* subclasses utilize a subscribe-publish protocol to update interested clients in the progress of image reading and writing.

4.1.2. Evidence of patterns

While the Image I/O API exhibits many examples of the OO principles described earlier, it makes use of

IIORegistry (not shown in Fig. 1 for space reasons). Only one registry instance can exist, so the class is responsible for keeping track of its sole instance. This is achieved with the *getDefaultInstance()* class method that returns the instance if it exists else creates it.

4.1.2.4. Abstract factory. The service provider interface hierarchy resembles that of the abstract factory. For example, to create *ImageReader* instances the *IIORegistry* is searched for *ImageReaderSpi* instances and the appropriate instance is selected for the format type of the image to be read. This spi instance is then used to create the *ImageReader* instance for that image format. The *ImageReaderSpi* is an abstract class responsible for instantiating instances of *ImageReader* subclasses. This controls and localizes the creation of *ImageReader* instances ensuring that the correct reader is created.

4.1.3. Framework extension

The key characteristic of frameworks mentioned earlier is the ability to tailor the framework for a given application while leveraging the core services insulated within the abstractions. The design pattern constructs discussed above contribute to this facility, but the greater contribution in the Image I/O API seems to be in the application of the broader OO principles. That is to say that sound object-oriented design is more evident than specific design patterns.

The influence of the OCP is clear in the consistent use of interfaces and abstract classes that allow users to specialize classes such as *ImageReader*, *ImageWriter*, *ColorModel*, *SampleModel* and service providers to support various image formats. This reliance upon abstractions also supports the DIP. *ImageWriter*

instances accept any image class that supports the *RenderedImage* interface rather than being dependent on concrete, or indeed more specialized abstract classes such as the *BufferedImage* class. This is also the case with regard to the listener classes. By conforming to standard interfaces any object can be updated with the progress of image reading and writing and the readers and writers have no knowledge of the implementation aspects of those clients obviating the need for future changes to support new interested observers (OCP at work again). The separate listener interfaces can also be considered as interface segregation as suggested by the ISP. Individual observers may be interested in reading progress, reading updates and reading warnings so can implement all three interfaces, rather than a single “readinglistener” interface, thus allowing the three aspects to vary independently if necessary.

Finally, the fact that most of the classes in the API are abstract classes, and therefore need to be subclassed and implemented by a framework user, the LSP is applied. Indeed, in almost all cases the associations and dependencies between classes in the package are at the abstract level therefore supporting the substitutivity of subclasses for their base classes.

4.2. Java 2D™ API

The Java 2D™ API enhances the imaging capabilities of the Abstract Windowing Toolkit enabling the development of advanced graphic libraries and image filters. It comprises six entire packages and parts of two others defining, in total, 127 classes and interfaces. The API supports three imaging models compared below in Table 1 [17].

Table 1
Features of Java 2D™ API supported imaging models (adapted from [17])

	Major interfaces/ classes	Pros	Cons
Push Model (producer/consumer)	<i>Image</i>	Processing driven by image availability	Requires transfer of complete images
	<i>ImageProducer</i>	Images processed incrementally	Complex programming interface
	<i>ImageConsumer</i> <i>ImageObserver</i>		
Immediate Mode (image buffer model)	<i>BufferedImage</i>	Simple programming interface	Requires memory allocation of complete images
	<i>Raster</i>	Commonly used model	Requires processing of complete images
	<i>BufferedImageOp</i> <i>RasterOp</i>		
Pull Model (pipeline)	<i>RenderableImage</i> <i>RenderableImageOp</i> (Java 2D API) <i>ImageConsumer</i> <i>ImageObserver</i> (Java Advanced Imaging API)	Stores/processes only required data Allows lazy evaluation	More complex programming interface More complex implementation

Given the overall size of the API this discussion will be limited to the framework aspects related to the immediate mode-imaging model. A partial class diagram containing the classes and interfaces associated with this aspect is provided in Fig. 2 and those associated with jpeg compression (the sun.com.image.codec.jpeg package of the 2D API) are shown in Fig. 3.

4.2.1. API description

The *BufferedImage* class and its associated classes (*ColorModel*, *Raster* and *SampleModel*) from the Image I/O API are included in the 2D API. Additionally, the 2D API includes predefined subclasses for the *ColorModel* and *SampleModel* for different types of image formats (*ComponentColorModel* and *ComponentSampleModel* for example). More interestingly, however, are the type hierarchies of the image operation classes (*RasterOp* and *BufferedImageOp*). Many developers new to object-orientation find such seemingly process-oriented classes in contradiction to the basic premise of

the paradigm; the encapsulation of data and behavior into discrete entities. It is important to note, however, the intent of the “Fine-grained objects” framework pattern described earlier—break objects down into increasingly finer granularities until further decomposition results in objects with no relevance to the domain. In this case it is clear that image transforms are very relevant to the domain, and what’s more, are likely to change in the future as new transforms are developed. In such cases it is important to encapsulate this potential variation. The API therefore defines several classes of image operations which implement both the *RasterOp* and *BufferedImageOp* interfaces (and one class, *BandCombineOp*, that implements only the *RasterOp* interface).

The JPEG compression aspects are also included here to identify how different codecs can be defined within the framework. The central class is the *JPEGCodec* factory that creates instances of encoder and decoder classes that implement the *JPEGEncoder* and

Fig. 2. Partial class diagram of Java 2D™ API (imaging classes and interfaces).

Fig. 3. Class diagram of com.sun.image.codec.jpeg package.

JPEGDecoder interfaces (indicated in Fig. 3 as *MyEncoder* and *MyDecoder*) providing each with a parameter class that encapsulates the tables and options necessary to control coding (classes that implement the *JPEGDecodeParam* or *JPEGEncodeParam* interfaces) a stream (*InputStream* and *OutputStream*) and an image class (*BufferedImage* or *Raster*).

4.2.2. Evidence of patterns

4.2.2.1. Abstract factory. The Abstract Factory (or, more appropriately in this case, Factory) is the most obvious example of a pattern in the 2D API. The *JPEGCodec* class is responsible for creating instances of encoders and decoders and with supplying these classes with the appropriate parameter, stream, and image classes. This approach ensures that the correct sets of classes are instantiated together (the correct parameter class for the coder class) and localizes the creation mechanism in case of future changes (OAOO principle).

4.2.2.2. Observer. The Observer pattern is also obvious in the API given the naming convention used. The *TileObserver* interface is an interface that must be implemented by any object interested in the state of tiles (modifiable or unmodifiable) in any object implementing the *WritableRenderedImage* interface, such as *BufferedImage* objects. This obviates the need for image objects to “know” about the implementation of those objects interested in the images current state thus allowing for new types to be defined that wish to respond to changes in image objects without modification of the existing software (the new types just have to implement the *TileObserver* interface, and add themselves to the list of observers of the image object).

4.2.2.3. Strategy. The strategy pattern is apparent in Fig. 2 where image processing operations have been encapsulated in classes that implement common

interfaces (*RasterOp* and *BufferedImageOp*). Clients that might encapsulate such transforms (*BufferedImageFilter*, for example) now delegate the processing to these classes thus allowing the transforms to vary independently, and providing support for dynamic changes in processing (since the interfaces are inherited the derived classes are substitutable for one another—LSP).

4.2.3. Framework extension

As in the case of the Image I/O API, the 2D API defines an extensible framework and therefore reflects the object-oriented principles described earlier. In general the preponderance of interfaces and abstract classes within the API supports the OCP and LSP ideals of separating interface from implementation, and embedding common and non-variant aspects in the abstract levels.

In particular the ISP is evident in having the image operation classes implement two interfaces, one for each type of client that may be operated upon (*BufferedImage* or *Raster*) and therefore allowing the two interfaces to vary independently. To extend an application for more transforms the developer need only to implement one or both of these interfaces in the new operation class.

Extension to support additional codecs is not as mechanized, however. Examining the jpeg package it is evident that no generic (abstract) class of codec is defined nor any interfaces for the codec elements. Nevertheless, the general structure of future codecs is clear: define a factory “codec” class that instantiates an encoder and decoder and supplies them with any appropriate parameters, within their own class, along with the necessary *InputStream*, *OutputStream*, *BufferedImage* or *Raster*. It is also worth noting that in the Java Advanced Imaging API [18] (not discussed here because of its volume) a more generalized structure for codec extension is defined.

5. Conclusions

In general software systems must cope with change or be rebuilt. Given that change is forced upon software systems almost continuously this exerts significant pressure upon the design. It is clearly undesirable to redevelop and redeploy a system whenever a new technology, standard, algorithm or device appears. This is exactly the situation in real-time imaging systems, however. As new image processing algorithms and standards are developed the software that support imaging systems must be modified and rebuilt. An alternative approach examined in this work leverages the widely documented advantages of object-oriented development. By applying some fundamental principles of good design a system can be constructed that is robust with respect to changing requirements, allows extension of functionality without modification to existing components and can be reused in any number of specific applications.

Two examples of such systems taken from the Java imaging APIs (Java Image I/O API and Java 2D™ API) have been described and the influence of the principles, and the more specific design patterns, is clear. The work also serves, therefore, as a demonstration of the practical application of design patterns, a compelling form of best practices, but it must be said that these are but examples of the fundamental principles in specific situations and are not the sole vehicle of reusable design.

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